

Safety of New Austrian Tunnelling Method (NATM) Tunnels

A review of sprayed concrete lined tunnels with particular reference to London clay



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This report, published in 1996, explains the problems in defining the New Austrian Tunnelling Method (NATM). It deals with the worldwide history of NATM failures and collapses and describes the legislation, the importance of a risk-based approach and describes a model for managing risk.

The report was produced in response to the collapse of three tunnels of the Heathrow Express Link.

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Introduction, scope and purpose of the review

Introduction

On 21 October 1994 and over the following days, three parallel tunnels being constructed as part of the Heathrow Express Rail Link, at Heathrow Airport near London, collapsed. The tunnels were being excavated in London clay and involved a primary lining of sprayed concrete. A permanent inner lining was due to be constructed at a later date.

The system of primary lining design and construction was stated to be the 'New Austrian Tunnelling Method' (NATM). It describes a variety of similar tunnelling techniques which may have their origins in Austria but are by no means confined to it. Tunnelling techniques described by some who use the word 'NATM' go beyond the Austrian definition. And although 'NATM' is used in the literature and throughout the tunnelling industry world-wide, there is no definition which is understood and agreed by all who use it. This review uses NATM to describe

'a tunnel constructed using open face excavation techniques and with a lining constructed within the tunnel from sprayed concrete to provide ground support often with the additional use of ground anchors, bolts and dowels as appropriate.'

This review is not about what term is used to describe the NATM process, (described in Part 1), but how such tunnels may be designed and constructed safely.

At the time of the collapse NATM was being used at two major locations on the Heathrow Express Project – at the Central Terminal Area (CTA) station where the collapse occurred and at Terminal 4 (T4). It was also about to be used on a separate project at Heathrow as part of the construction of a Baggage Transfer System between T4 and the CTA. NATM projects were also underway in central London as part of the Jubilee Line Extension Project (JLEP) for the construction of tunnels near Waterloo and London Bridge stations.

Immediately after the collapse these projects voluntarily suspended their NATM works as a precautionary measure. HSE requested that the work should not recommence until the project teams could demonstrate that they could adequately control the risks to both the workforce and the public.

The Health and Safety Commission (HSC) requested the Health and Safety Executive (HSE) to carry out a two part investigation. Mr M S Nattrass, HM Chief Inspector of Construction was asked to lead.

HSE was asked:

- First, to consider whether there were any broader health and safety implications concerning both the construction of NATM tunnels in the UK, and the safety of the finished tunnel using this method when compared to tunnels constructed using different tunnelling techniques. This review meets that objective.
- Second, to investigate the causes of the Heathrow collapse and publish a report of the findings. **That report will be separately published in due course and this report is written without prejudice to it. No implications either explicit or implicit should be drawn from the contents of this report**

with respect to the circumstances of the collapse nor to the causes of the collapse, nor to the roles or responsibilities of any person (legal or otherwise) involved in it.

HSE's Response

HSE set up a Project Board to oversee the work of the HSE's investigation team, to review proposals for restarting NATM work, and to consider the wider health and safety implications of NATM. Board and team members are listed at appendix 1.

Consultation with the industry

Whilst undertaking the review, HSE;

- published a discussion paper on 5th Dec. 1994 entitled 'The use of NATM in soft ground in the UK' which is reproduced at appendix 2, and took account of the comments received, and
- sponsored a meeting (Muir Wood 1995) held at the Institution of Civil Engineers on 25th Jan. 1995, which was chaired by Sir Alan Muir Wood and involved representatives from those most closely concerned with advising clients on the use of NATM in the UK, and
- engaged in extensive discussions with those who were associated with the proposals to recommence NATM work, and
- commissioned a research report from Dr CPM Snee of Bradford University into post-construction auditing of the sprayed concrete lining for quality. This report is being published separately by HSE as a contract research report.

Scope of the review

This review whilst considering some aspects of general tunnel safety is principally concerned with the construction of tunnels in urban areas in soft ground. It focuses specifically on health and safety issues; it is not intended to be a design code nor a manual for those undertaking such work. No research has been undertaken into tunnel collapses which have occurred using any other tunnelling methods.

On NATM projects issues of design and construction are closely linked. This review does not attempt to treat them separately. All parties should therefore take note of the advice given in this review and ensure that they act upon it.

The review considers the NATM process as a whole from conception through to completion of construction, and does not consider directly the contractual and management arrangements. It describes the features of the NATM process which have significant safety implications and concentrates on the functions to be carried out not on the functionaries.

Purpose of the review

HSE hopes that this review will:

- stimulate a wider debate about the safety of NATM and related forms of tunnelling incorporating sprayed concrete linings and open face excavation techniques;
- inform clients and their professional advisors about detailed matters that require attention from a health and safety point of view;

- stimulate discussion within the industry about the adequacy of present engineering practices to effectively control tunnelling risks and to ensure safety;
- promote the development and improvement of engineering codes and design and construction practices applied to this work;
- stimulate appropriate research;
- enable workers and their representatives better to appreciate the hazards of NATM tunnelling;
- inform others, such as local authorities, not directly concerned with tunnelling work itself to enable them to appreciate how they might be affected by it.

Summary of findings

The review is in 6 parts:

- Part 1 – the NATM process;
- Part 2 – world-wide review of NATM safety;
- Part 3 – UK health and safety legislation;
- Part 4 – safety principles;
- Part 5 – designing for safety;
- Part 6 – management arrangements.

HSE's principal conclusions are given at the end of this summary.

Part 1: The NATM process

The 'New Austrian Tunnelling Method' is defined by an Austrian code. It describes a variety of similar tunnelling techniques which may have their origins in Austria but are by no means confined to it. Tunnelling techniques described by some who use the word NATM (pronounced 'Natam') go beyond the Austrian definition. And although NATM is used in the literature and throughout the tunnelling industry world-wide, there is no definition which is understood and agreed by all who use it.

This review uses NATM (written in this form) to describe:

'a tunnel constructed using open face excavation techniques and with a lining constructed within the tunnel from sprayed concrete to provide ground support often with the additional use of ground anchors, bolts and dowels as appropriate.'

In London clay NATM tunnels almost always use reinforced sprayed concrete linings alone.

NATM is a descriptive term; it is not a definition. This review is not about what term is used to describe the NATM process, (described in Part 1), but how such tunnels may be designed and constructed safely.

Part 2: World-wide review of NATM safety

Detailed comparison of the overall level of risk of NATM with other forms of tunnelling has not been undertaken. Each particular tunnelling method may introduce certain risks while removing others. And such risks are specific to the individual location. Any attempt to compare risks between tunnelling methods adopted in differing locations would therefore be of little value.

World-wide NATM incidents

HSE has sought to establish the record of NATM incidents and collapses throughout the world. 39 significant NATM incidents are documented. More have been reported and it is likely that more have occurred but are unrecorded. As the records of incidents and tunnels built are incomplete it is not possible to form any views on incidence failure rates.

The *number* of incidents reported in recent years has increased. This might be attributable to a number of factors if:

- NATM is increasingly being used in more demanding environments;
- NATM is being used by those unfamiliar with the technique;
- there are inherent problems with NATM tunnel construction;
- hazards are not being adequately identified, managed and controlled;
- there is over-confidence in the method;
- there is more open reporting of failures.

The literature tends to blame either the ground or the workers or both, but rarely looks further and examines the NATM design, and construction methods and the systems of work.

NATM provides no inherent support for the tunnel heading should ground collapse into the tunnel. A crown hole may then develop above the tunnel. If the tunnel is shallow, and especially if the ground is permeable and water logged, a crater-like depression may form in the ground surface. In urban areas this may result in a high consequence event, especially for the larger diameter tunnels, which are commonly constructed using NATM.

Heading collapse is frequently attributed to unstable ground conditions, ignoring the fact that if a more appropriate construction method had been selected, collapse could have been avoided. The cause of the collapse is, therefore, not the ground but the use of the wrong construction method in the ground conditions which existed.

NATM lining failures do occur but they are not well publicised, and tend to be poorly documented. This imbalance in reporting makes it difficult to establish the overall level of risk, and as a result the risk of lining failure may be underestimated.

The world-wide data show that NATM tunnels, especially in soft ground in urban areas, may, when they collapse, result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment. (See photos 1 – 4.)

Recent NATM work in the UK

Since the Heathrow collapse, HSE has scrutinised over 30 NATM proposals, ranging from small-scale to substantial works. Except for the smallest and simplest jobs HSE found that there were, at the outset, significant deficiencies in the proposals. Some technical aspects of NATM design and construction were poorly understood, in particular the heading stability including both the excavated face and the incomplete lining, and the possible effects of compensation grouting.

Each project had the benefit of NATM advisers of international standing to assist them and it may therefore be reasonable to conclude that the deficiencies noted fairly reflect the international state of NATM tunnel design and construction.

NATM tunnels require the deployment of considerable skill and care in their investigation, planning, design construction and monitoring if they are to be safely constructed. The majority of the skills required are not unique to NATM.

After assessing the recent proposals for NATM construction in London, HSE has established that there is no intrinsic reason, provided careful account is taken of the advice contained in this review, why NATM work should not proceed in safety.

However, the list of deficiencies noted by HSE reflects many matters previously reported in the literature which leads to failures. HSE is seriously concerned that those introducing this technique, and their NATM advisers, into potentially high risk locations seem not to have adequately taken account of past experience.

If further NATM projects involving new teams of clients, designers and construction contractors are to proceed safely, all involved should be in no doubt of the complexity of the task. To be certain that an appropriate level of safety has been achieved for their own employees and the public, a rigorous and critical examination of the design and construction proposals must be carried out before construction starts.

Safety of completed NATM tunnels

Taking account of the historical record and HSE's considered analysis of in-service issues, there is no evidence to suggest that tunnels built with NATM linings, when finally completed and fully commissioned, are inherently less safe than those constructed by other means. There is no reason why they should not be regarded as being safe for use as any other type of tunnel.

Part 3: UK health and safety legislation

In the UK the legal responsibility for the safety of workers and the public is generally placed on those who create the risk.

The Management of Health and Safety at Work Regulations 1992 (MHSWR) place a duty on every employer to carry out a suitable and sufficient assessment of the risks to which people at work, and others, may be exposed with a view to identifying the measures which need to be taken to comply with legal requirements.

Successful management of risk depends on the identification of hazards, the assessment of risk, and the determination of risk control measures, in accordance with the statutory risk control hierarchy. Low probability high consequence events should be considered.

The Construction (Design and Management) Regulations 1994 (CDM) came into force on 31 March 1995, 5 months after the collapse at Heathrow. It is therefore not yet possible to assess the full impact that these regulations will have on a UK NATM project in practice.

Design under CDM includes specification, so those who specify NATM tunnelling methods have the legal duties of designers. The design for each element of a NATM tunnel should be fully developed before work on that element commences. Uncertainty will remain but to meet legal requirements all foreseeable areas of uncertainty should be identified, and the significance of deviations from expected performance determined in advance.

Any tunnel construction system may be legally acceptable provided that, so far as is reasonably practicable, adequate measures are taken to eliminate or minimise foreseeable risks by good design, and the necessary management and mitigatory measures are introduced to ensure that residual risks during construction are controlled and kept at acceptable levels.

The existing statutory provisions provide a comprehensive system for the regulatory control of risk. HSE has concluded that there is no need for further legislation specifically to address the risks from NATM.

Part 4: NATM safety principles

Part 4 provides advice on generally applicable NATM safety principles.

A tunnel may give rise to individual risk to workers and members of the public. A tunnel may also give rise to a societal risk if a collapse has the potential for injury to the public or significant damage to the built or natural environment. The maximum tolerable risk to any member of the public should be substantially lower than the maximum tolerable risk to workers in any industry. Events which could lead to failure should be discoverable in time to enable action to be taken to recover from the emerging situation, and to ensure safety at all times.

Tunnels should, as far as possible, be located away from areas of high consequence. Where this is not possible, particular attention should be paid to the means of mitigating the consequences of the hazards. There may be locations where the consequences of collapse no matter how remote the event, would not be acceptable. In such cases, if construction is to proceed at all, methods would have to be used which effectively eliminate the risk of collapse.

Whether a risk is tolerable or not is essentially a matter of judgement. This depends on confidence that all hazards have been identified; all reasonably practicable steps have been taken to assess, reduce and control risk; and the consequences of any serious mishap can be kept to a minimum.

High consequence events (such as face collapses or lining failures involving breakthroughs to the surface) should be considered in addition to the more likely events with lesser consequences.

Safety of the NATM process is heavily dependent on systems of management and work. People have to make complex judgements to achieve quality in many differing types of work, often under difficult site conditions. In essence safety is dependant on 'human factors'. Therefore if NATM is to be undertaken safely it is essential that those managing the process understand how human failure happens, what can be done to prevent it, how it can be detected and corrected, and how to recover.

Each duty-holder should analyse the key decisions that need to be taken to achieve the successful completion of a NATM project. Many of the tasks required to design and construct a NATM tunnel safely require a high degree of competence from the staff and workforce at all levels. Those employed on safety critical tasks should be assessed for competence and suitable training provided. Everyone involved should understand the key factors which might lead to high consequence events and their role in achieving effective risk control.

NATM design is intimately involved with construction and should consider the whole process, not just the end product. Designs which take account of ease of construction, or 'buildability', will greatly facilitate the achievement of quality, and will lead to a better product and improved safety. Designs and specifications should be reviewed for buildability before being released for construction.

The achievement of quality is essential if a NATM project is to be completed successfully. Quality assurance can play an important part in an overall system of risk management and control.

Part 5: Design for safety

Part 5 gives advice on safety principles in the context of NATM tunnel construction with particular reference to London clay. And it provides advice on how the risk may be either eliminated, or reduced, and residual risks controlled to acceptable levels. A risk-based approach to design and management is required to reduce uncertainty.

Many NATM failures have been attributed to unexpected ground conditions. The main safety objective of ground investigation for NATM is to identify all possible ground conditions so that the likelihood of encountering unexpected ground conditions is negligible. To reduce the risk, ground investigations to urban areas must ensure that the likelihood of meeting unexpected conditions of a critical nature can be excluded. Ground investigation data must be kept under constant review and reinterpreted as more information becomes available, to maintain an up to date prediction of the ground which the tunnel is likely to encounter. There is no technical reason why unforeseen ground conditions should be encountered in London clay during construction of a NATM tunnel.

Those involved in a NATM project should seek to take advantage of technological and technical progress which offers opportunities for improving working methods and materials and making them safer. A technology review should be undertaken to assist the selection of the most appropriate technologies so that the designer can then use them to best effect.

Typically two design procedures have been adopted for the design of a NATM tunnel, design by calculation, including semi-empirical methods, and prescriptive design. These two procedures have been supplemented by the observational method applied during the construction phase. Design by calculation uses conceptual models based on analysis which is believed, within reasonable bounds of accuracy, to represent the real behaviour. It is customary to apply 'factors of safety' to the value of the variables input to the analysis. These factors are intended, in part, to allow for the uncertainties in the design process. Prescriptive design is based on a distillation of prior construction experience which is not project specific. It may be necessary in situations where conceptual models are not available. And it may also be adopted for well-tried design details which are difficult to design by calculation. For most NATM projects there is insufficient local experience to provide the necessary confidence in a totally prescriptive design approach.

The dimensions, strength and articulation of the structure should be chosen so that the structure can withstand the likely loading. A robust design, which is essential, is one where the risk of failure or of damage, to the structure is extremely remote during its design life.

Normally, during construction, the behaviour of NATM tunnels is monitored. The monitoring procedure adopted is often described by the proponents of NATM as an application of the 'observational method'. A European code makes it clear that the observational method is a process in which a pre-determined 'design is reviewed during construction' i.e. it is not a safety procedure as such. It also makes it clear that a plan of contingency actions should be prepared before construction work starts. Such plans must clearly relate to the possibility that behaviour could be outside acceptable limits. The objective of monitoring under the observational method is 'to allow contingency actions (planned before construction is started) to be undertaken successfully'. Design review is a process of critical examination of product performance; review is not a process for design modification as work proceeds.

Monitoring during construction should be undertaken to ensure safety. Hazards such as the potential failure modes of the tunnel lining should be considered in detail. Additional monitoring may be required where there are safety implications for others.

NATM monitoring produces a large amount of data. Management and timely processing is crucial to safety. Tunnel collapses have occurred where this has not happened and there has been insufficient time for contingency plans to be implemented. Monitoring data should be reviewed frequently to ensure that adverse trends and events are identified in time.

Design development and verification may show that design modifications are desirable. These should only be necessary if unforeseen circumstances arise. Design modifications should only be used to enhance a robust design.

Most failures occur during or soon after excavation within the tunnel ahead of the completed lining, (i.e. ahead of ring closure). This part of the tunnel is called the 'heading' (i.e. the tunnel face and incomplete lining).

The sequence of excavation adopted for NATM tunnels usually requires steep temporary faces. London clay is not sufficiently strong to support excavated faces indefinitely and faces more than a few metres in height will fail. The face may stand unsupported for a short time and 'stand up' times of about 18 hours have been reported. However this is dependent upon several factors some of which are difficult to evaluate. For safety, 'stand up' times should be considered as 'fall down' times and conservative values must be considered.

NATM tunnels require a significant 'stand up' time so that the initial ground support can be erected. If a collapse occurs with open faced tunnelling techniques such as NATM, there may not always be sufficient time to install emergency support and prevent a collapse. For safety, the tunnel heading must be designed so that it is stable at all times. As safety cannot usually be achieved by monitoring the heading, every stage of its construction must be properly designed.

In urban areas, the control of surface settlement is necessary to prevent damage to the built environment above the tunnel. Compensation grouting is a technique used to control the settlement of the ground surface while a tunnel, not necessarily a NATM tunnel, is constructed below. Proposals for activities to control settlement, such as compensation grouting, which may adversely affect tunnel construction must be evaluated and allowed for in the design. Compensation grouting should be taken into account. Its effects on the tunnel should be predicted to minimise risk.

A sprayed concrete lining acts as a thin flexible membrane. There is a complex interaction whereby the ground both loads and supports it. The lining relies upon the ground to prevent damaging deformation. The modes of failure observed in sprayed concrete linings in NATM tunnels are summarised in table 3. A sprayed concrete lining is inherently more susceptible to damage by ground movement than a segmental lining. Therefore, the prediction of changes in the shape of the tunnel periphery with time, and due to adjacent construction, is more critical to a NATM sprayed concrete lining.

NATM requires the on-site formation of a high quality concrete based product under difficult site conditions. During design, detailed consideration should be given to the practical difficulties of constructing NATM lining so that quality is satisfactory from the start of construction. If safety is to be assured, there is no opportunity for a 'learning curve' to bring the lining construction to a satisfactory standard.

Part 6: Management Arrangements

Effective management is central to the successful delivery of a NATM project. A risk-based control strategy is essential. NATM tunnels can be constructed without major incident as witnessed by those that have been successfully completed. Where failures have occurred, the world literature suggests that poor management has been a significant contributory factor. Although NATM may be complex and technically demanding, it does not require skills not already available in the UK. Competency of the NATM team is crucial and should be assessed.

The complexity of major projects involving NATM is likely to result in each duty holder having a substantial management team. Individual team structures may not always be readily compatible with others. This can hinder communication, co-ordination, control and co-operation both within and between the teams.

Some contractual arrangements divide design work between designers appointed by constructors and lead-designers appointed by clients. This typically occurs when the NATM lining design is constructor led as an element of 'temporary works'. This may inhibit the development of an integrated design approach.

Design and construction, including on-site monitoring, are closely intertwined in tunnelling projects. Difficulties may arise if this is not recognised in the way contracts for services and construction are let. NATM is an interactive process that intimately binds together the design of the permanent and temporary works.

Health and safety risks associated with NATM tunnel construction are significantly affected by the planning and outline design stages of projects. Due consideration should be given to risks early in design so that they may be reduced.

If NATM is a possibility, the particular advantages and disadvantages should be considered. In the range of ground conditions where NATM is normally used, alternative methods are available and should be considered.

If the presumption of a NATM based solution has been made at an early stage in the design process and not further considered, or not considered at all, until the post-construction tender appointment of a NATM designer, there may be fundamental issues with wide-ranging implications to address against a background of limited knowledge, pressures of limited time and resources already expended on tunnel design.

Any limitations imposed by designs on construction sequences and programmes must be clearly understood. Safe working methods and contingency and emergency plans should be developed. Suitable management structures and systems should be determined to deal with the residual risks. These, and other matters, should be integrated into health and safety plans developed for the construction phase.

Although this review deals with major safety hazards created by the NATM process, other hazards will need to be taken into account.

Residual risks necessitate contingency plans and emergency procedures to ensure that people within the tunnel and elsewhere are protected.

Principal HSE conclusions

- 1 Major NATM collapses have occurred world-wide. This finding and recent scrutiny of proposals for NATM in the UK leads HSE to conclude that some safety critical aspects of NATM design and construction have been poorly understood, and past experience has not been adequately taken into account.
- 2 NATM tunnel collapses in urban areas can result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.
- 3 There will be locations where the consequences of collapse are unacceptable. In such cases alternative solutions should be adopted.
- 4 There is always some degree of uncertainty in tunnelling design and construction. This can be significant with NATM. A risk-based approach to design and management is required.
- 5 Safety risks are greatest in tunnel headings. Open faces, a feature of NATM, are hazardous. Linings are more vulnerable to collapse before the ring is closed.
- 6 Ground investigations throughout must ensure that there is no likelihood of meeting unexpected conditions of a critical nature.
- 7 A robust design is essential. Design for each element should be fully developed before construction of that element commences. Design modifications should only be used to enhance a robust design.
- 8 The 'observational method' is a process in which a pre-determined design is reviewed during construction. It is not a method of design or design modification.
- 9 An integrated approach should be taken to the design of permanent and temporary works. Design should consider the whole process of NATM tunnel construction.
- 10 Monitoring is of limited value in the heading and does not ensure face stability. Therefore, every stage in the excavation of the heading and construction of the lining should be designed.
- 11 The safety of completed sprayed concrete linings depends on monitoring and data interpretation. The design should determine the monitoring regime and contingency actions.
- 12 The achievement of quality is essential if a NATM project is to be completed successfully.
- 13 'Buildability' (ease of construction) should be considered in design and construction planning.
- 14 Contingency plans and emergency procedures are required to deal with adverse events.
- 15 NATM is heavily dependent on avoiding human failure.
- 16 NATM tunnels require the deployment of considerable skill and care in investigation, planning, design, construction and monitoring. Clients, designers and constructors should not underestimate the complexity of the task they will face before and during construction.
- 17 Competency of the NATM team is crucial, and should be assessed.
- 18 NATM projects do not require skills not already available to the UK construction industry.
- 19 **Provided careful account is taken of all the issues in this review, it has proved possible for NATM work to proceed in safety.**
- 20 **The existing statutory provisions, and in particular CDM, provide a comprehensive system for the regulatory control of risk including the assessment of competencies. HSE concludes there is no need for further legislation specifically to address the risks arising from NATM.**
- 21 **Tunnels built with NATM linings, when finally completed and fully commissioned, are as safe as those constructed by other means.**

Part 1 - The NATM process

1.0 Introduction

1 This part explains the origins of the term NATM, describes the NATM process in simple terms as an aid to understanding, and goes on to describe some of the technical features of NATM tunnels.

1.1 Origin of the term NATM

2 The first use of the English language term 'New Austrian Tunnelling Method' (N.A.T.M.) appears to be in a series of three articles by Professor L von Rabcewicz published in the magazine *Water Power* in November and December 1964 and January 1965 (Rabcewicz, 1964). These articles described the use of a relatively thin sprayed concrete lining, together with other strata reinforcement, to stabilize tunnels excavated in rock. One of the articles refers to the construction of a tunnel in Venezuela, in 1957-58, using 'shotcrete and rock bolting'.

3 The 1964/64 articles in *Water Power* derive from a lecture given in German by Professor von Rabcewicz at the 13th Salzburg Colloquium in 1962 (Sauer, 1988).

4 The tunnel design and construction described by Professor von Rabcewicz involved several fundamental principles of ground mechanics and the interaction of the ground with a tunnel lining. He stated that the sprayed concrete lining must be designed, in both shape and material properties, so that it was capable of moving with the ground to develop a stable condition with adequate factors of safety. He drew attention to the need in design to consider the stresses and strains in the ground surrounding the tunnel, in any ground reinforcement, as well as in the lining. The use of tunnel deformation measurements to confirm that a stable condition had been achieved was also described.

5 The design and construction techniques described by Professor Von Rabcewicz allow the ground to move towards the tunnel in a controlled manner, thereby developing shear stresses which act in conjunction with the tunnel lining. By mobilizing the strength of the ground in this way, substantial reductions are made in the tunnel lining or support systems required to achieve stability. By the adoption of such techniques, developed in differing circumstances by many tunnelling engineers, the cost of tunnel construction is significantly reduced. Professor von Rabcewicz's particular form of design and construction techniques were widely adopted by other engineers and the term 'New Austrian Tunnelling Method' or N.A.T.M. was used to describe this type of tunnel construction work.

6 The N.A.T.M. was first used in an urban soft ground situation for construction of the Frankfurt Metro in 1968.

7 Inevitably, as the popularity of the technique grew and it began to be practiced more widely, some confusion developed as to what was meant by N.A.T.M. The term N.A.T.M. is used to describe a variety of similar tunnelling techniques which may have their origins in Austria but are by no means confined to it. The Austrian Society of Engineers and Architects have issued a leaflet in 10 languages setting out a definition. In the English version, paragraph 1 states:

"Definition: The New Austrian Tunnelling Method constitutes a method where the surrounding rock or soil formations of a tunnel are integrated into an overall

ring-like support structure. Thus the formations will themselves be part of this supporting structure”.

8 The leaflet continues to define N.A.T.M. by giving, in addition four main principles, three general principles, eight specific principles and twenty two illustrated principles.

9 The articles in *Water Power* by Professor von Rabcewicz were effectively a 1964 ‘state of the art’ report on tunnelling in rocks using open face excavation techniques and a tunnel lining or ground support system constructed in the tunnel. The articles were not written in isolation and, as several authors have pointed out, many of the ideas and construction techniques described recur throughout the history of tunnelling (Sauer, 1988).

10 Since 1964, significant advances have been made in both the design and construction of tunnels, and in the engineering sciences relevant to such work. The ‘state of the art’ is not fixed, and any attempt to define the tunnelling process is likely to attract criticism. This has happened and one notable critic of N.A.T.M. has claimed that the structure of thought behind N.A.T.M. rests, not on an established theoretical foundation, but rather on two fundamental misconceptions (Kovari, 1993). Referring to the definition of N.A.T.M., he comments that “... tunnelling without the structural action of the ground is inconceivable ... and ... that the idea of the ground as a structural element is inherent to the concept of a tunnel”.

11 Despite criticisms, the work ‘NATM’ (pronounced ‘Natam’) is used in the literature describing tunnel design and construction, and throughout the tunnelling industry world-wide. But from the way in which the term is used, it seems probable that many of the authors either are not aware of or do not mean to imply any precise technical definition by its use. It is clear that despite the Austrian definition of the term N.A.T.M. the tunnelling techniques described by those who use the word ‘NATM’ go beyond the Austrian definition and, although the word ‘NATM’ is used in common parlance, it has no definition which is understood and agreed by all who use it.

12 This review uses the term N.A.T.M. to denote the ‘New Austrian Tunnelling Method’ as defined by the Austrian code and the word NATM (written in this form) throughout the text to describe

‘a tunnel constructed using open face excavation techniques and with a lining constructed within the tunnel from sprayed concrete to provide ground support often with the additional use of ground anchors, bolts and dowels as appropriate.’

13 For NATM tunnels in London clay the use of sprayed concrete linings alone predominates. The range or scope of the term NATM is not the same as that of N.A.T.M. In some situations, which do not apply in London clay, a N.A.T.M. tunnel may be constructed without a sprayed concrete lining; ground support in such cases is provided by ground anchors, bolts and dowels etc.

14 NATM is a descriptive term; it is not a definition. It does not describe in detail any tunnel design or construction method. This review draws on the work of others who have also used the term N.A.T.M. in imprecise ways which would also be included in the term NATM. However, the principal issue for this review is not about what term is used to describe the tunnelling process but how NATM tunnels are designed and constructed safely.

1.2 A brief outline of the NATM construction process

15 In urban areas, NATM tunnel construction usually starts from a previously constructed vertical shaft. This shaft will be used for access by persons and plant and for the removal of excavated material out of the tunnel.

16 In a typical NATM tunnel the cross-section (or tunnel face) is divided up into a number of smaller faces. There are typically three, the crown, bench and invert (figure 1). This can be increased to six (figure 2) by adopting designs with a temporary central wall and advancing first one half of the tunnel, called the side gallery, around 15 metres ahead of the remainder, the enlargement. The temporary wall is constructed as part of the side gallery and is then removed as the enlargement is formed.

17 Excavation is incrementally advanced in steps, or rounds, of about one metre to a fixed pattern. Shotcrete, a special quick-setting concrete mix sprayed at high pressure, is used after each incremental excavation to form a new panel to the lining. A 50 mm sealing layer is generally first applied to the excavated face on which the new panel is to be formed. Shotcrete is then generally applied in two layers, each reinforced by steel mesh, to form a NATM lining typically 200 to 400 mm thick. The second layer may be applied before advancing the excavation or it may be delayed until a later stage in the cycle.

18 Shotcrete not adhering to the lining is known as 'rebound' as it normally arises from material rebounding from the panel, particularly from any reinforcement during shotcreting. If incorporated into the lining it will adversely affect the strength and integrity of the completed work. It should be treated as waste material and requires clearing from the work area.

19 Steel lattice girders can be incorporated into the lining. These may typically be in the crown panels or fully circumferential. They may provide some limited measure of support to the excavated crown prior to shotcreting and shortly thereafter when the shotcrete is weak. They also provide assistance in profiling the tunnel and in achieving the correct shotcrete thickness.

20 Excavated material is usually placed temporarily on the completed tunnel invert to provide a running surface for plant during further construction.

21 The speed of construction is important in limiting ground settlement as once the ring is closed significant ground movement normally ceases. The ring is closed when the last panel of shotcrete in an advance is formed. This is typically some five rounds behind the leading cut. (figure 1)

22 A secondary or final tunnel lining is usually added at a later date inside the primary sprayed concrete NATM lining. The secondary lining is usually formed of cast in-situ or sprayed concrete, but may also be of cast-iron segments.

23 During construction two safety issues are paramount:

- First, the advancing face should be stable so that it does not collapse;
- Second, the lining should be capable of supporting the ground during its incremental construction and thereafter.

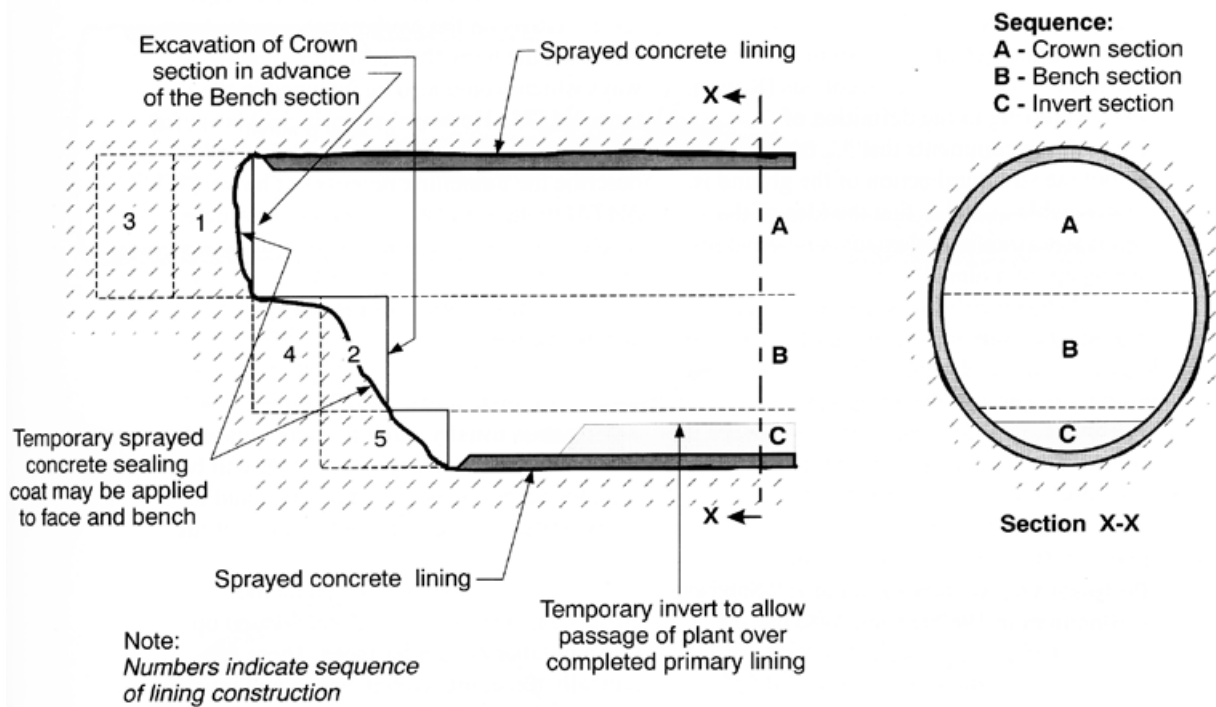


Figure 1 Example of NATM tunnel excavated in 3 partial cross-sections

1.3 Some technical features of NATM

Face stability

24 A fundamental technical requirement of a NATM tunnel is the potential for the ground in the excavation face to remain stable for sufficient time for the lining or ground support system to be constructed and the tunnel advanced. Clay (like many soils) has a property commonly referred to as its 'stand-up' time. It is a term that, for a clay, relates to the ability of the face to be self-supporting, due to the development of a reduced pore water pressure, following excavation. It is a relatively short-lived effect (typically between 18-24 hours in London clay) after which time the ground will collapse. In some materials other than London clay, it may be possible to increase the stand up time by ground treatment, such as grouting or ground freezing, prior to excavation. More importantly, it is a concept that cannot always be relied upon in practice due to factors including variability in the geology, such as naturally occurring planes of weakness, and changes in water content.

25 In particular, naturally occurring inclined joints in the clay can cause large lumps, known as 'greasy-backs' to fall from the face. Their size is dependent on the size of the face and the orientation of the planes of weakness. Although it is unlikely that a progressive collapse affecting those at the surface will occur, a falling greasy-back may cause major injury and, potentially, a fatality to a worker. The risk of injury is greater where the greasy-back falls from higher up the face and may be reduced by:

- battering or doming the face;
- leaving unexcavated ground as a 'dumpling' against the face;
- reducing the size of the 'advance';
- placing a sealing coat of shotcrete on the face and,
- more comprehensive ground support measures such as ground anchors and forepoling (spiling).

26 Forepoling involves the insertion of rods or tubes into the extremities of the crown face so that the rods are supported from within the tunnel and project above and beyond the area to be excavated (see also glossary).

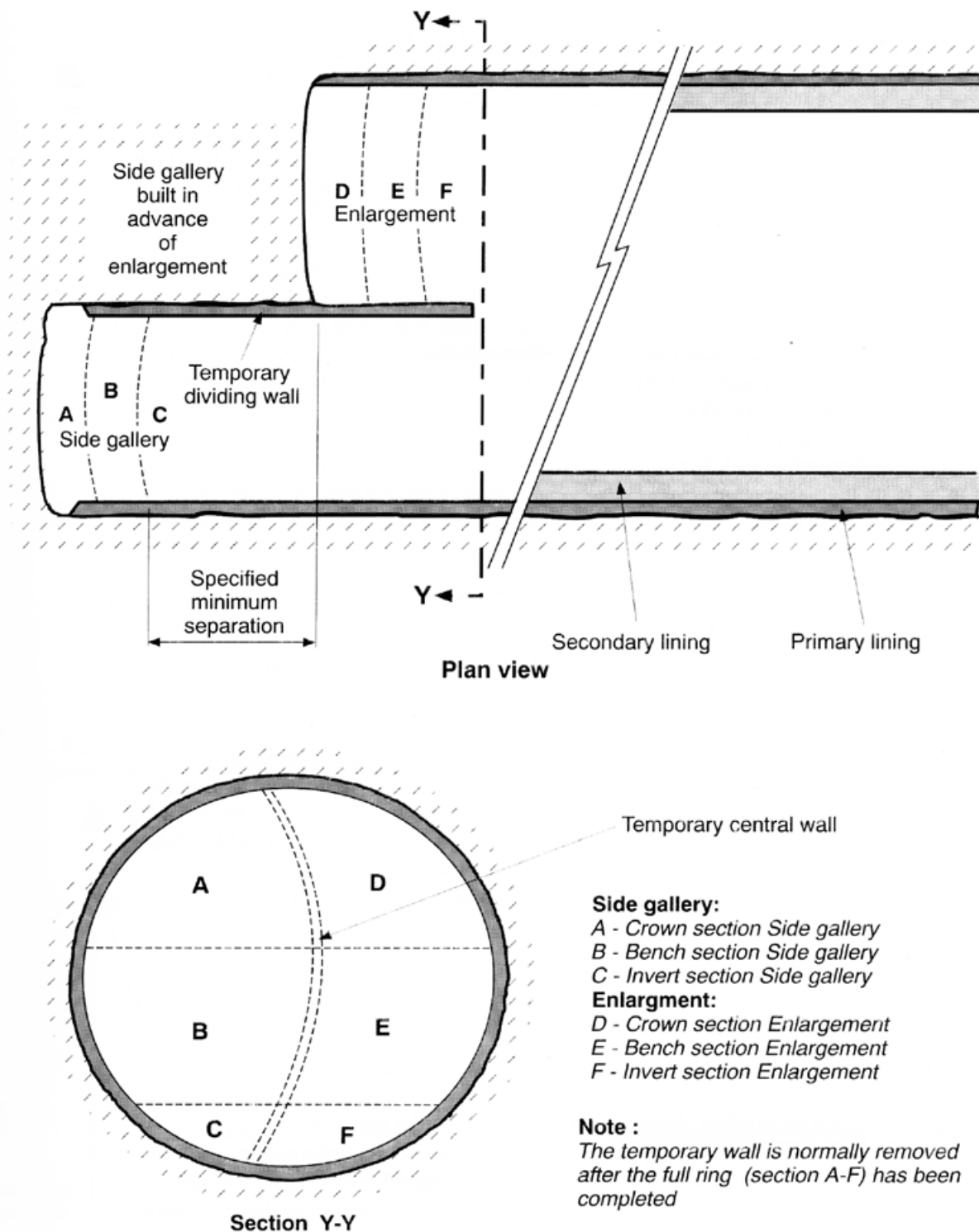


Figure 2 Example of NATM tunnel excavated in 6 partial cross-sections

27 An irregular feature such as an inclusion of granular material into the crown could cause a progressively collapse especially if it is water bearing.

28 At the tunnel face the redistribution of stress and movement of the ground towards a tunnel excavation occurs in three dimensions and hence movement will occur before the lining or ground support system can be constructed. Further, in order to support the ground, the lining or ground support system must be deformed thereby allowing more ground movement to occur. The support provided (or load carried) is a function of the strains induced in, and the stiffness of, the lining or ground support materials. The ground movement towards the tunnel typically results in settlement at the surface. The total amount of ground movement also includes inward movement at the face, often the predominant factor for NATM tunnels in clay.

Performance of the lining

29 The primary NATM lining should be capable of supporting the ground during its incremental construction and thereafter. It normally ceases to have any structural purpose when the permanent lining has been formed within it at some later stage.

30 During the early stages of constructing a ring, the crown panels carry a developing load from the overburden. The lower edges of the panels bear on the clay. Widened bearing strips, known as 'elephant's feet' (figure 3), are sometimes provided along the full length of the panels.

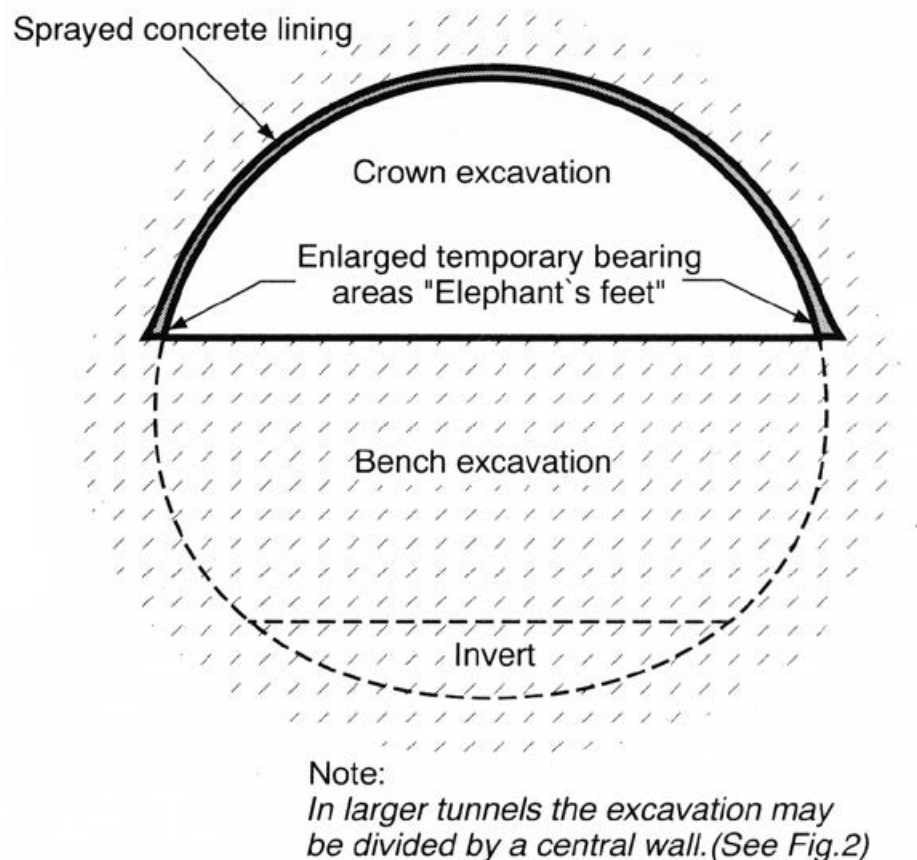


Figure 3 'Elephant's feet' providing support to the incomplete lining

31 Loads on a lining are transferred into compressive forces acting around the circumference of the thin-shell structure. Typically the linings are unable to resist ground deformation, hence the lining must be able to tolerate movements induced by the ground.

32 In situations where ground deformations have no significant effect on nearby structures or utilities, the cost of the tunnel support may theoretically be reduced by allowing greater ground deformation so minimizing the ground load on the lining or ground support system. In other situations, such as those that usually apply beneath urban areas, the tunnel support may have to accept a larger ground load so as to limit the ground deformations and surface settlements to within acceptable limits. The variation of ground load with deformation and the timing of construction of the tunnel lining are illustrated. (figure. 4)

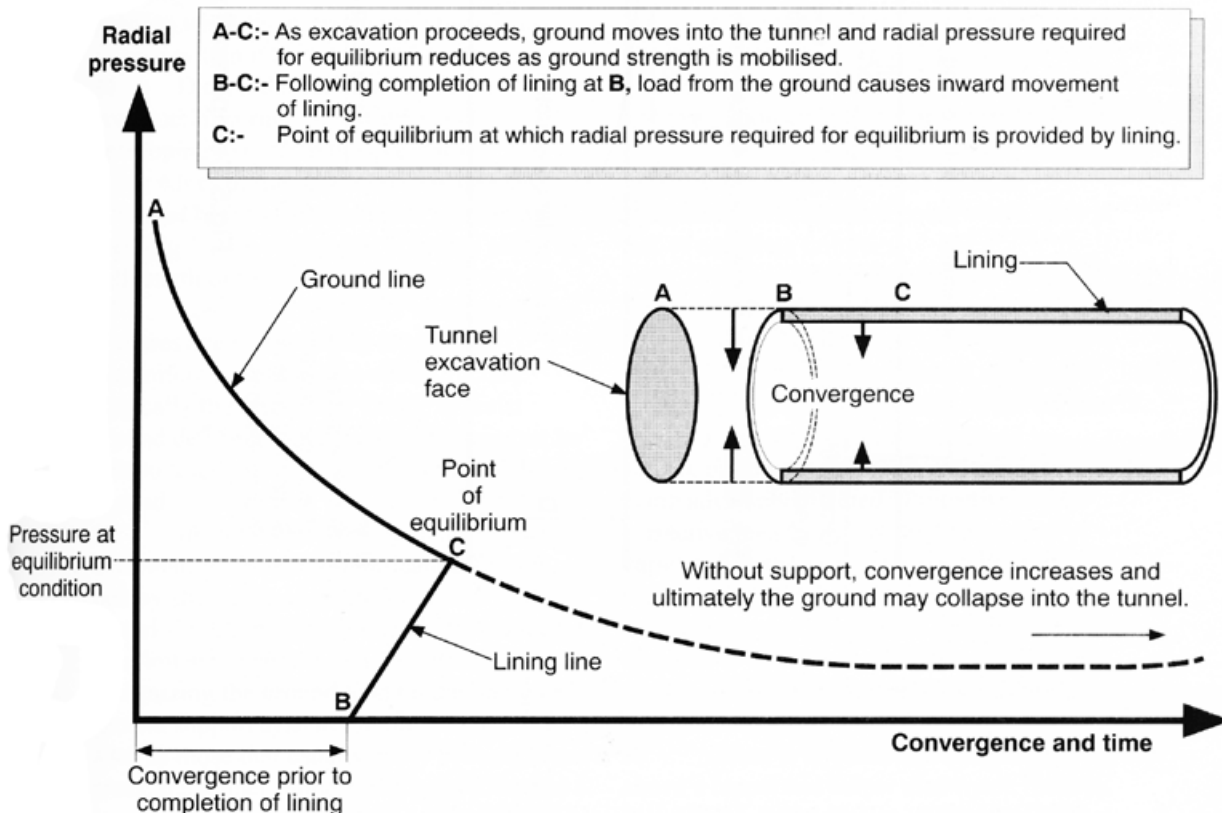


Figure 4 Ground lining intersection: conceptual diagram

Monitoring

33 Though the principles of tunnel excavation and ground support can be stated simply, it is extremely difficult to make accurate predictions of the strains and hence of the shear strength mobilised within the ground to support the tunnel. In part this is because the ground strains are significantly affected by the rate and sequence of tunnel construction. Hence, it is difficult to optimise the lining or ground support system by design calculation alone, and empirical rules, which have been developed from prior tunnel construction experience, are used in some cases.

34 Monitoring of the deformation of the lining or tunnel perimeter is undertaken to obtain regular, accurate and up-to-date information about the performance of the tunnel. Its correct and timely interpretation is crucial for both the purpose of design optimisation and for safety. Data collection and evaluation must be sufficient to enable measures, such as additional support, to be implemented before a tunnel collapse mechanism develops to a point where there is risk of complete failure.

Settlement control measures

35 When tunnelling work is undertaken through soft ground, settlement of the surface occurs. Excessive settlement can lead to surface buildings, structures and services being adversely affected. Protective and/or corrective measures may then be needed. A variety of methods may be available. One method used widely in

London is compensation grouting. This process is intended to ameliorate the effects of settlement caused by ground loss resulting from the tunnelling work.

36 Grout is injected into the ground above a tunnel and below man-made features. It is delivered to the point of injection through long pipes. Holes or ports through the pipe wall, covered by neoprene sleeves, form non-return valves. These pipes are known by their French name 'tubes-a-manchettes' or TAMs. A large number of TAMs is generally called for. They can be at differing levels to create a thickened injection zone. TAMs are typically installed from purpose constructed shafts.

37 The provisions for individual grout injections and the layout of the TAMs and the associated ports are determined in the initial design to ensure that settlement can be controlled in the required areas of ground. The amount, timing and location of grout injections is determined from settlement monitoring. In most cases multiple phases of grouting are used incrementally to control ground settlement as it occurs.

38 A first stage approach is to inject some grout before tunnelling affects the ground. This has become known as 'pre-conditioning.' It is said to stiffen the ground by closing fissures, so that subsequent grouting can have immediate beneficial effect. Small rises detected in the structures being protected are taken as an indication that the ground has been pre-conditioned. Further grout is then injected as the tunnel is constructed so that settlement is adequately compensated by the addition of grout into the ground, hence the origin of the term 'compensation grouting'. (figure. 5)

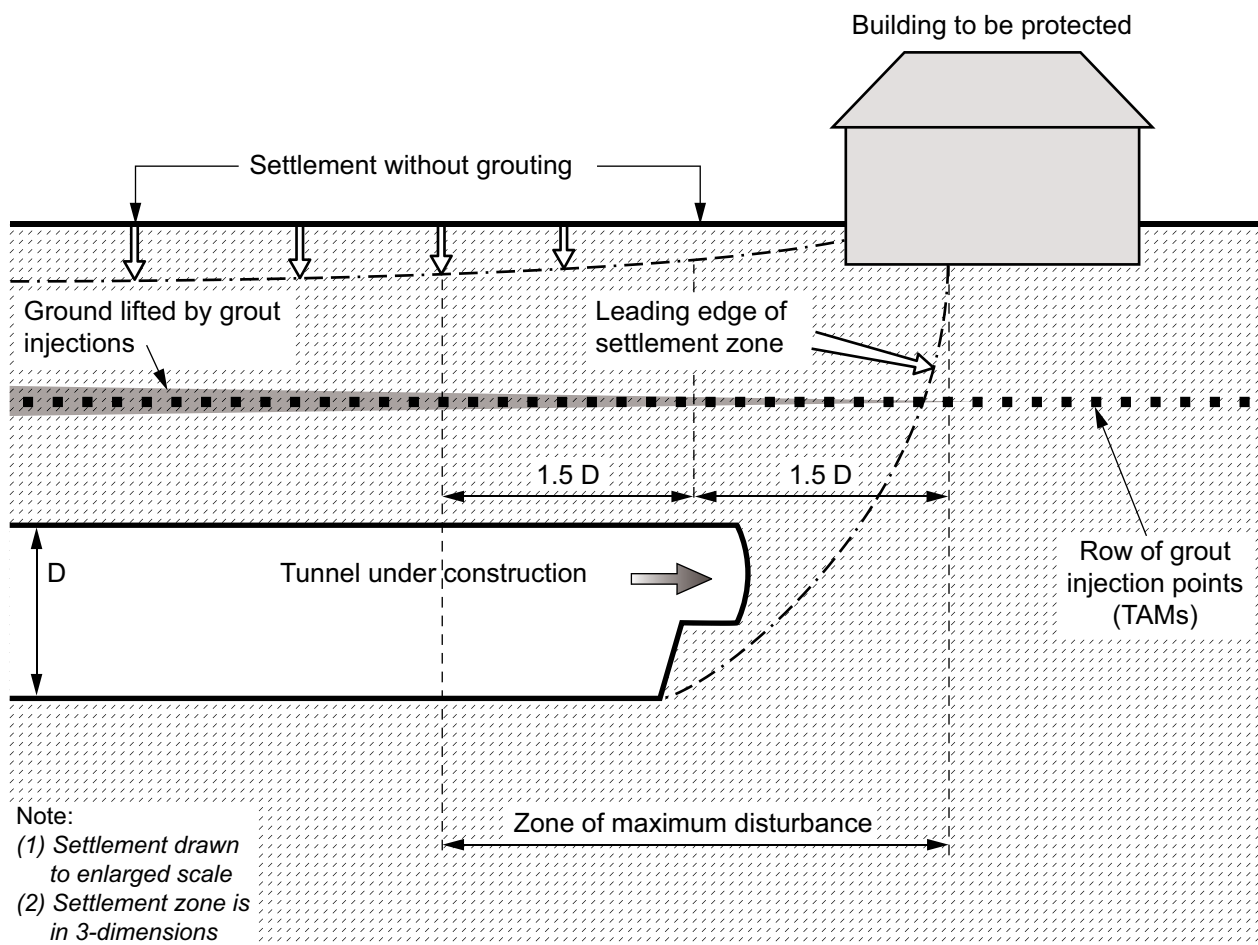


Figure 5 Compensation grouting

Summary

39 In summary, the following technical features are usually found in the construction of NATM tunnels:

- an open excavation face with no direct support to the excavated surface, (excavation is by point attack methods, road header etc., or drill-and-blast);
- to ensure the stability of the excavated face in larger NATM tunnels, excavation is carried out in a number of sections to reduce the face size. Further reduction of face size may be achieved by excavating tunnels in a number of discrete headings, (typically, such tunnels may be excavated in two stages, crown and invert, or three stages with a bench between crown and invert.);
- a wall lining or ground support system which is constructed in the tunnel soon after excavation and which can be incrementally strengthened if the need arises, (typically sprayed concrete linings are used in 'soft' ground with ground anchors, dowels or spiles providing temporary support as required.);
- an in-tunnel monitoring system to measure the deformation of the lining and or tunnel perimeter, (other monitoring devices such as pressure cells to measure the stresses in the sprayed concrete lining may also be provided);
- where surface movements are critical there is a system for monitoring and control of surface settlement, (typically this includes compensation grouting);
- monitoring and analysis of the deformation data to confirm that ground and lining movement has stabilised and to allow appropriate remedial actions to be taken.

Part 2 - World-wide review of NATM safety

2.0 Introduction

40 This part of the review considers the world wide experience from significant NATM incidents. It:

- describes the extent of NATM incidents world-wide and analyses information from published and other sources about the causes of failures;
- gives examples of incidents where there were significant consequences;
- considers HSE's direct experience in dealing with proposals for NATM work submitted following the collapse at Heathrow;
- discusses the findings about the nature and consequences of major incidents and the reasons for them;
- reviews the data about safety of completed NATM tunnels; and
- draws conclusions.

41 Numerous literature sources refer to the world wide record of successful NATM tunnel construction, particularly in the last 10 years. They also, however, describe mechanisms for collapses and often suggest causes and remedies. It has not been possible to establish the numbers of NATM tunnels that have been completed without incident. Papers on the investigation of collapses assert that such occurrences form a very small part of the total NATM work.

2.1 Comparison of NATM with other tunnelling techniques

42 No detailed comparison of the overall level of risk of NATM tunnelling with other forms of tunnelling has been undertaken. Hence it is not possible to conclude whether NATM tunnel construction is more likely to give rise to major hazards than other tunnelling methods. Each particular type of tunnelling method may introduce certain risks while removing others. For example NATM may introduce risks associated with the installation of the primary support lining close to the excavated faces, with attendant health risks from dust and noise, but may avoid risks associated with the use of tunnel boring machines or other dangers such as the transport and mechanical handling of heavy precast segments. And the risks associated with any choice of tunnelling method are specific to the individual location making a comparative study of risks between tunnelling methods adopted in differing locations valueless. Rather, it is for those proposing to undertake a particular project to carry out a comparative risk assessment, specific to that location, based on the best information available using techniques such as those outlined in other HSE guidance. (ref. 42)

43 This review concentrates on the record of failures of NATM tunnels rather than the health and safety hazards which can arise to workers in the tunnel from other causes. Comparison of the health and safety hazards from NATM with those that may arise from other tunnels types is not attempted in detail. The essential point is that all these hazards should be understood, and appropriate risk control measures introduced.

2.2 Review of NATM incidents, mechanisms and causes

44 HSE has undertaken an extensive literature search supplemented by information from other sources in order to establish the record of NATM incidents and collapses throughout the world (tables 1 & 2).

Incidents

45 Table 1 lists 39 significant NATM incidents, gives the literature reference, outlines the circumstances of the incident and gives the consequences of failure, where known. Some are illustrated in figures 7 to 14, and photos 1 to 4. Not all failures have been reported and therefore the list is an incomplete record. The true number of incidents is likely to be significantly in excess of this figure. Indeed some authors refer to collapses but give insufficient details to identify locations or dates. To avoid the risk of double counting, these have not been listed. Nonetheless, it is thought to be the most comprehensive catalogue of NATM incidents so far published.

46 Incidents have been included where the collapse or incident has been described in the literature as a 'cave-in'. 'Collapse' in the descriptive context of this table and in this review is taken to mean a sudden, uncontrolled release of the ground resulting in the loss of the most or all of the cross-section of a tunnel or a substantial fall of material. Where it is known that the ground unravelled to the surface this has been indicated. This is described as a daylight collapse although it may not have been possible to see into the tunnel itself from the edge of the crater at the ground surface.

47 The data on incidents (table 1) shows that:

- 38 significant NATM incidents out of the 39 identified have occurred in the second half of the 30 year period of NATM's existence i.e. from 1980 to 1994 inclusive;
- the ratio of collapses in urban areas compared to rural areas is 2:1;
- some projects have experienced multiple collapses;
- incidents are not confined to countries with little prior experience of NATM;
- the consequences of collapse for the public, infrastructure and the built environment are consistently high in urban areas.

48 In addition to those listed in table 1, a further 71 incidents in 65 tunnels have been reported in Japan between 1978 and 1991, mainly in hard rock. (Inokuma et al 1994). Some were quite small. 15 incidents were in the range 50 – 500m³, and 3 were over 1000m³. Two collapses resulted in surface craters.

49 Many incidents have been reported from countries with previous experience of NATM tunnel construction. Therefore it seems inappropriate to attribute the increases in the number of incidents solely to the lack of prior experience. The amount of NATM tunnel construction has almost certainly increased and this will influence the number of collapses reported to some extent. As there are no complete records of incidents, nor of tunnels built, it is not possible to form any views on incidence rates for failure. The *number* of incidents reported in recent years has increased. This might be attributed to a number of factors, if:

- NATM is increasingly being used in more demanding environments;
- NATM is being used by those unfamiliar with the technique;
- there are inherent problems with NATM tunnel construction;
- hazards are not being adequately identified, managed and controlled;
- there is over-confidence in the method;
- there is more open reporting of failures.

Table 1 Table of NATM tunnel incidents (including collapses)

NO	DATE	LOCATION	REMARKS AND LITERATURE REFERENCES	REPORTED CAUSE	NATURE OF REFERENCE OR SOURCE OF INFORMATION	BRIEF CIRCUMSTANCES	PROJECT	URBAN OR RURAL	CONSEQUENCES OTHER THAN ADDITIONAL PROJECT COST AND TIME
1	October 1973	Rail tunnel, Paris, France	Collapse <i>Muller 1978</i>	A ₆ , A ₈	Published article 1978	Example of 'numerical' errors in that convergence measurements not processed and acted upon. (Reference to Massenberg Tunnel.) Consequence unknown. No indication if in urban environment.	Rail	?	?
2	18 December 1981	São Paulo metro, North-South link, Brazil	Sudden serious instability during construction. Noise and lining cracking <i>Kochen et al 1987</i>	A ₁	Conference paper presented in Paris in 1987	No collapse but cone of settlement at surface buildings (urban area) max value of 120 mm. 6 m dia; 200 mm shotcrete lining with 8 m overburden. Change of ground conditions within face and change from drained to undrained conditions are likely to have affected stability. Timber propping introduced to prevent full collapse.	Urban metro	Urban	Buildings demolition
3	1983	Santana Underground Railway, Brazil	Cave-in	Insufficient detail available	Private correspondence	First use of NATM in Brazil. No casualties, but collapse progressed to street level where cave-in depth was 80 cm. Residential suburb.	Rail	Urban	6 Houses demolished
4	13 November 1984	Landrücken Tunnel, Germany	Collapse <i>Nussberger & Juttmann 1987</i> <i>John, Wogin & Heissel 1987</i> [Fig. 7]	A ₈ , A ₁₀	a) Published article 1987 b) Conference Paper 1987	11 km tunnel through various caving-in erosion ground features of tubular or chimney like forms. Total of 47 such zones encountered. First point of failure was shearing of the base of the crown and walls due to overload-rest of collapse sequences shown on diagrams. Consequence unknown but delays due to recovery operations made up in the end.	Rail	Rural	
5	1984	Bochum Metro, Germany #1	Collapse <i>Laue and Sager 1987</i>	B ₁ , A ₇ , A ₉	Conference Paper 1987	Daylight collapse 7.5 m cover, 150 mm lining thickness, 6.5 m dia. tunnel. Collapse within 30 minutes. Ground movement involved 300 cu.m in urban/street area. Collapse put down to redistribution of load from front excavation. Crown advance shortened afterwards.	Rail	Rural	Urban disruption
6	17 January 1985	Richthof tunnel, Germany	Collapse <i>Engels and Auber 1987</i>	A ₁	Conference Paper 1987	Crown and bench drill and blast rock. 20 m overburden in rural area. Tunnel collapse 18 m with surface crater 11 m by max of 6 m deep. 3 months to re-excavate.	Rail	Rural	
7	1985	Bochum Metro, Germany #2	Collapse <i>Laue and Sager 1987</i>	A ₁	Conference Paper 1987	Daylight collapse to street level. Fissuring and water blamed for ground instability at the face. Cavity of 30 m ³ formed under road as a result of ground collapse into tunnel.	Metro	Urban	Urban disruption
8	August 1985	Kaiserau Tunnel, Germany	Collapse <i>Wallis 1990 (1988)</i>	A ₄ , A ₅	Published article 1988 & 1990	"Almost daylight" collapse. 100 m in from portal, full heading and bench under 25 m cover. "Collapse occurred during excavation of the bench". No further details. No indication of consequences except change in excavation sequence to include two side drifts. 4 months delay.	Rail	Rural	
9	17 February 1986	Krieberg Tunnel, Germany	Collapse <i>Wallis 1987 (1990)</i> <i>Leichnitz & Schlitt 1987</i> [Fig. 8]	A ₃ , A ₁₀	a) Published article 1987 & 1990 b) Conference Paper 1987	3 km tunnel through sandstone. Tunnel with two side drifts and top crown section. Collapse of partially completed lining adjacent to the face thought to be due to local oversteering due to sand lenses and water. Progressive collapse of crown and 2 drift tunnels backwards for 55 m. Very substantial surface damage in rural area. Collapse within 30 minutes.	Rail	Rural	Large surface damage (rural)
10	Before 1987	Munich Metro, Germany #1	Collapse <i>Weber 1987</i> [Fig. 9]	C ₂	Published article 1987	Tunnel collapse and inundation and flooding of shaft. Competent cover immediately outside the shaft was not 1.5 m as planned but inadequate 80 cm and upper waterlogged strata broke through. Full collapse to surface-movement of 450 m ³ involved.	Metro	Urban	Urban disruption, excavator buried
11	Before 1987	Munich Metro, Germany #2	Collapse <i>Weber 1987</i> [Fig. 10]	A ₁ , A ₁₂	Published article 1987	Cave-in up to surface - 5 m overburden 30 m ³ of gravel. Collapse in part due to omission of distance spacers between crown arches. Crown excavation underway. Water level below tunnel.	Metro	Urban	Urban disruption
12	Before 1987	Munich Metro, Germany #3	Collapse <i>Weber 1987</i> <i>Kovari and Weber 1991</i> [Fig. 11]	A ₁	a) Published article 1987 b) Conference Paper 1991	300 m ³ collapse to street surface as a result of local thinning of competent overburden (marl). Water level above tunnel. Face failure. Test boring vertically upwards behind the face at the first ring revealed adequate cover. Forepoling had just ended as it was thought no longer necessary. Excavator buried.	Metro	Urban	Urban disruption. Excavator buried.
13	Before 1987	Munich Metro, Germany #4	Collapse <i>Weber 1987</i> <i>Kovari & Weber 1991</i>	A ₁ , A ₁₂	a) Published article 1987 b) Conference Paper 1991	300 m ³ collapse to street surface as a result of local thinning of competent marl cover over the tunnel. Erosion feature encountered and water logged material flowed into the tunnel. Immediately prior there had been a danger zone including soffit lowering. Work was speeded up after this and test borings were not made which could have revealed the problem. Water level above tunnel.	Metro	Urban	Urban disruption
14	Before 1987	Munich Metro, Germany #5	Collapse <i>Weber 1987</i> <i>Kovari and Weber 1991</i> [Fig. 12]	A ₁ , A ₁₂	a) Published article 1987 b) Conference Paper 1991	200 m ³ collapse at street level. Local thinning of marl cover was anticipated and the waterlogged ground above was being treated by the formation of an arch of frozen ground. However due to poor construction there was an unintended gap of unfrozen ground around which the cave-in occurred.	Metro	Urban	Urban disruption. Excavator buried

Table 1 Table of NATM tunnel incidents (including collapses) continued

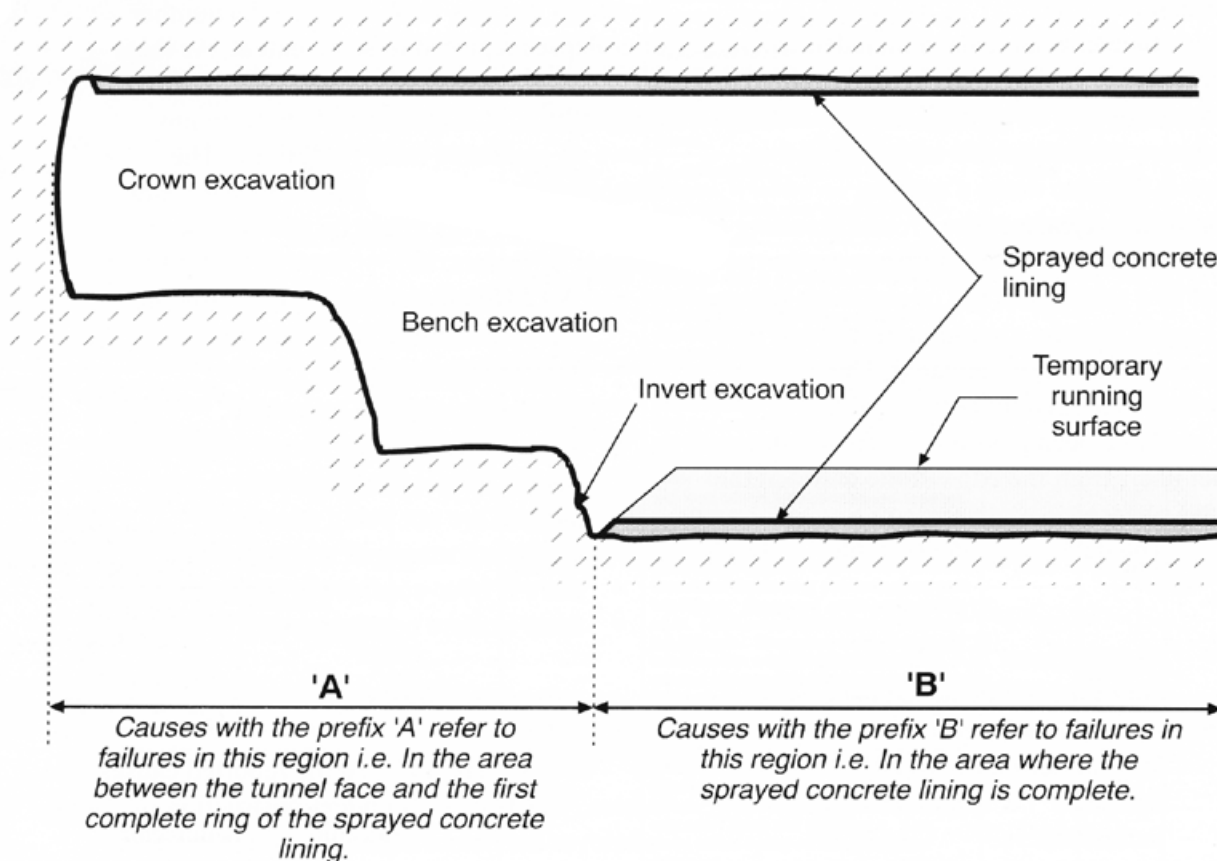
NO	DATE	LOCATION	REMARKS AND LITERATURE REFERENCES	REPORTED CAUSE	NATURE OF REFERENCE OR SOURCE OF INFORMATION	BRIEF CIRCUMSTANCES	PROJECT	URBAN OR RURAL	CONSEQUENCES OTHER THAN ADDITIONAL PROJECT COST AND TIME
15	Before 1987	Munich Metro, Germany #6	Material transfer <i>Weber 1987</i> <i>Kovari and Weber 1991</i>	No collapse	a) Published article 1987 b) Conference Paper 1991	Very unusual tunnel to tunnel material transfer of 40 cu m. One tunnel under 0.95 bar caused blowout into unpressurised tunnel 40 m away. Defective invert in secured tunnel. Loss of air to second tunnel put stability of first tunnel at risk and fears of settlement to station immediately above first tunnel. Restoration of air pressure prevented to collapse/further damage.	Metro	Urban	
16	Before 1987	Weltkugel Tunnel, Germany	Cave-in <i>Schrewe 1987</i>	A ₃ ,	Published article 1987	Cave in of 50m ³ while crown drainage underway. Sandstone (heavily weathered) described as 'friable' destabilised to semi-stable and very brittle given the slightest mechanical effect. High convergence up to 245mm but over 5 months period. Crown drainage ceased after cave-in but detailed circumstances not clear.	Rail	?	
17	1987	Karawanken Tunnel Austria/Slovenia	Large inflows and severe deformations <i>Martin 1991</i>	No collapse	Published article 1991	Hardrock tunnel with high tectonic stresses in Alps. Worst period has been with the high tectonic stresses combined with poorer quality rock. Maximum total convergence before stabilisation has been 120cm in places. Tunnel, driven oversize to cope with severe squeezing. Shotcrete lining in crown cast into 5 segments with gaps in between to allow for closure. Also intrudes of methane. "Shotcrete and rockbolts serve mainly to rectify the ground deformations" says author.	7.5 dia Road tunnel, 7.8km long	Rural mount-ains	
18	Before 1988	Kehrenberg Tunnel, Germany	Serious surface settlements. Propping installed to prevent tunnel collapse <i>Wallis 1988 (1990)</i>	Not collapse (A ₃)	Published article 1988 and 1990	Two photos of timber propping of distressed crown sections. Fault zone predicted but effect not fully appreciated. Water and sand overcome by dewatering and side drift construction. Length involved only 30m. Consequence unknown apart from delays and additional costs.	?	Rail	
19	1988	Michaels Tunnel, Germany	Collapse during pilot tunnel enlargement	(A ₁₀) Not enough details	Private correspondence	Collapse due to change in ground conditions which had been predicted to be a problem. It seems the support conditions for the strong rock were continued unmodified in the weaker ground. Lack of supervision and predictions party to blame. 11m span. Collapse during tunnel enlargement from pilot.	?	?	
20	8 Jan 1989	Karawanken Tunnel Austria/Slovenia	Collapse <i>Maidl 1993</i>	A ₁ , A ₁₁	Published article 1993	Huge collapse involving 4000m ³ in hard rock tunnel. Combination of very high water pressures (up to 36 bar) and loose broken rock in fault zone causing reduction in shear strength. Post Christmas break factor here and redistribution of stresses. Some suggestion that old records could have given warning.	Road	Rural	
21	27 September 1991	Kwachon Tunnel, Korea	Collapse [Photo 1]	Not enough information	Newspaper articles	Collapse of subway tunnel construction in soft ground described as "clay". 15m overburden. Huge crater formed at the surface. Four workers trapped for 26 hours but rescued unhurt.	Metro	Rural	
22	17 November 1991	Seoul Metro, Phase 2 # 1 Korea	Collapse <i>Park and Lee 1993</i>	A ₁	Conference paper 1993 Newspaper reports	Daylight collapse up to ground surface which involved the embankment of a river. Roads collapse and gas main serving 5000 households was fractured. Ground described as "weathered rock or clay". 5 press cuttings. Crater 20m x 15 m x 4 m deep. Water from river into tunnel.	Metro	Rural	Fractured gas main
23	27 November 1991	Seoul Metro #2 Korea	Collapse affecting buildings and utilities <i>Park and Lee 1993</i> [Photo 2]	A ₁	Conference paper 1993 Newspaper reports	Substantial daylight collapse, 10 days after #1. Park and Lee describe as "sliding failure" ie rock movements along joint planes at the unsupported face. Street crater 28 m dia maximum. 3 buildings collapsed and communications, water, gas and sewerage broken. Incident subject to special 214 page report by Korea Civil Engineering Society. Newspaper report blames changing ground conditions and that boreholes were only taken at 100m intervals. 28m overburden.	Metro	Urban	Substantial urban disturbance.
24	1992	Funagata Tunnel, Yamagata Prefecture, Japan	Collapse	(C ₁)	Private correspondence	12 m wide 8m high 15 m overburden. Collapse due to water and loose ground-water due to rain and snow melt. Face of sand and gravel. Crater at ground level 6 m deep 4 m wide.	Road	Rural?	
25	12 February 1992	Seoul Metro, Phase 2 #3 Korea	Collapse <i>Park and Lee 1993</i>	A ₂	Correspondence Paper 1993 Newspaper report	Daylight collapse. While excavating with road header soil and water flowed into tunnel area through old investigationdrilling hole. Gas and water utilities fractured and photos show massive rafic disruption.	Metro	Urban	Utilities broken, traffic problem

Table 1 Table of NATM tunnel incidents (including collapses) continued

NO	DATE	LOCATION	REMARKS AND LITERATURE REFERENCES	REPORTED CAUSE	NATURE OF REFERENCE OR SOURCE OF INFORMATION	BRIEF CIRCUMSTANCES	PROJECT	URBAN OR RURAL	CONSEQUENCES OTHER THAN ADDITIONAL PROJECT COST AND TIME
26	30 June 1992	Lambach Tunnel, Austria	Collapse <i>Vavrovsky and Schubert 1995</i>	A ₆	Conference paper 1995	Daylight collapse. No dimensions and no indication of Urban or rural areas. Failure due to local weakness of bench-forewarning of which had been given by differential movement of crown abutments one month earlier. Failure of bench and ground above caused miners to be trapped in crown excavation some distance ahead. Rescued by borehole.	Rail	?	
27	7 January 1993	Seoul Metro, Phase 2, Korea #4	Collapse <i>Park and Lee 1993</i>	A ₁	Conference paper 1993 Newspaper report	Daylight collapse to street level due to ground inflow (soft rock) combined with high ground water pressure. Face collapse. Photo of road crater - traffic suspended. Close to buildings.	Metro	Urban	Road distribution
28	2 February 1993	Seoul Metro, Phase 2, Korea #5	Collapse <i>Park and Lee 1993</i>	A ₁	Conference paper 1993	Daylight collapse when "weathered rock" failed at face and groundwater and material flowed in. 10m wide elliptical shaped area subsided at river waterside. 6 "heavy equipments" buried.	Metro	Urban no buildings	Loss of construction plant
29	Feb/March 1993	Seoul Metro, Phase 2, Korea #6	Collapse <i>Park and Lee 1993</i>	A ₃	Conference paper 1993	Daylight collapse. Very little detail available. In weathered rock in the crown area involving rock movements along joint planes.	Metro	Likely Urban	
30	Feb/March 93	Seoul Metro, Phase 2, Korea #7	Collapse <i>Park and Lee 1993</i>	A ₃	Conference paper 1993	Daylight collapse. Very little detail available. In "residual clay" in the bench area where there was "shear failure".	Metro	Likely Urban	
31	March 1993	Chunggho Tunnel, Taipei, Taiwan	Collapse	A ₁	Private correspondence	15m dia. road tunnel under mountain. Collapse said to be because of 'bad ground conditions'. Length of tunnel collapse involved 100 m and collapsed area took 2 years to repair. Other NATM collapses have occurred in Taiwan.	Road	Rural	
32	November 1993	Road Tunnel at Avenida Santo Amaro, São Paulo, Brazil	Collapse [Photo 3]	A ₁ , A ₇ , A ₃	Private correspondence, Newspaper reports	Very low overburden in "fissured hard clay". Crown too far in advance reduced safety level and unstable convergence measurements resulted. Face collapse led to collapse of drain which filled tunnel with water which then piped over to other tunnel with sink hole in between. Power supplies cut to 500, 000 people. Massive urban disruption.	Metro	Urban	Huge urban disruption
33	1993	Road tunnel ("Poggio Fornello"), Tuscany, Central Italy	Severe deformations (?collapse) <i>Pelizza et al 1994</i>	A ₃	Conference paper 1994	Severe asymmetrical deformations of crown excavation due to poor geomechanical rock conditions. Excavated cross-section 104 sq.m. Local propping installed to prevent full collapse. Excavation method changed to full section with 35-40 No. glass fibre grouted pipes installed in the face each up to 14m long. Low overburden of 25m max.	Road	?Rural	
34	April 1994	Cardvalho Pinto Tunnel, Brazil	In-service remedial works, portal failure during construction	C ₁	Private correspondence Newspaper report.	Only case discovered of in-service repairs to completed NATM tunnel. Cracks appeared and subsequent investigation discovered gaps between primary and secondary linings. Repairs involved removing areas of secondary lining and replacing it. Also portal failure during construction (date unknown).	Road	?	Traffic disruption
35	30 July 1994	Montemor Road Tunnel, Portugal #1	Collapse <i>Wallis 1995</i>	Not clear (A ₃)	Published article 1995	Tunnel is twin bore, each 20m wide for three traffic lanes. This collapse concerned the 6m high, 19.5m wide upper heading in the north tunnel with 20m overburden. 45m length of the tunnel collapsed with a resulting 18m dia. surface crater. Collapse was "sudden and unexpected". Precise collapse sequence unclear - said to have been influenced by a leaking small dia. water main above the tunnel construction.	Road	?	?
36	1 August 1994	Montemor Road Tunnel, Portugal #2	Collapse <i>Wallis 1995</i>	Not clear (A ₁)	Published article 1995	This collapse concerned pilot drive (6 drift total cross-section) of south drive causing 5m diameter surface crater. Precise collapse mechanism unclear. Likely to have been directly linked to collapse #1 26 hours earlier.	Road	Urban	
37	August 1994	Galgenberg Tunnel, Austria	Collapse <i>Schubert & Riedmuller 1995</i>	A ₁	Technical paper	Tunnel within heavily faulted area. Crown cross-section 60m ² ; total cross-section 110m ² . Lining incorporated 'deformation slots' to cope with squeezing rock. Rock outburst from face occurred 'suddenly' and with no early warning. Collapse volume estimated as 700m ³ . Investigation did not uncover any construction defects.	?	?Rural	One death
38	20 September 1994	Munich metro, Germany	Collapse 4 killed 27 injured <i>Tiefbau 4/95</i> [Photo 4]	A ₁	Published article 1995 and Newspaper reports	Metro construction in marl under waterlogged gravels. Cover to tunnel thought to be adequate but it thinned locally and its water and gravels fell into tunnel. Bus travelling at street level fell into substantial crater which formed very quickly. One worker on surface and several bus passengers drowned. Half face excavation at collapse.	Metro	Urban	Deaths. Urban disruption
39	21 October 1994	Heathrow Airport, London	Three tunnel collapse being investigated by the Health and Safety Executive	← to be subject of a separate HSE Report →					

Reported causes

50 HSE has analysed the reported causes where NATM tunnels under construction, whatever the nature of the excavated material, have collapsed. These are shown in table 2. A number are taken from papers by Lechnitz W and Schrewe F (1987), Schrewe F and Maidl R (1987), Muller-Salzburg M (1978) and Kuhnenn K (1995) where the location is not known. This supplements the information in table 1.



Causes with the prefix 'C' occur elsewhere as described.

Figure 6 Location of the causes described in Table 2

51 Table 2 lists the causes under three principal locations (figure 6):

- Category A – *Heading collapses* which have occurred, initially at least, in the area of the NATM tunnel heading in front of the first completed ring;
- Category B – *Completed lining collapses* i.e. in the area where the sprayed concrete lining is complete; and
- Category C – *Other collapse locations*.

52 Using the best information from the published reports causes of failure have been attributed to each of these collapses. Some collapses appear to have been due to a combination of more than one cause, and this has been reflected in both tables. In a few cases there was insufficient information to allocate a specific failure cause. Table 2 establishes as comprehensive a set of causes as possible, and shows which occur most often.

53 Analysis of table 2 leads to the following conclusions about the causes of NATM collapses:

- 19 combinations of causes and locations have been identified;

- Category A1 predominates; the most frequent (18 incidents) is unstable ground at the tunnel heading;
- Category A collapses are more common than categories B and C;
- 1 incident in category B was due to a sprayed concrete lining failing progressively from an initial heading failure;
- Incidents in category B have not been as well documented as those in category A;
- Category B incidents are therefore under-represented in both table 2 (in detail) and table 1 (in number);
- In category C there were 2 incidents during portal construction, including one from a shaft break out.

Table 2 Reported cause of collapse (see figure 6)

CAUSE OF COLLAPSE		LOCATION	AUTHORS
A-In the area of the NATM tunnel heading between the excavated face and the first completed ring:			
A1	Collapse of unstable natural ground at the excavated face.	São Paulo 83, Richtof, Bochum #2 Munich #2, Munich #3, Munich #4, Munich #5, Karawanken Seoul #1, Seoul #2, Funagata, Seoul #4, Seoul #5, Chunggho, Sao Paulo 93, Munich 94, Montemor #2, Galgenberg.	Schrewe & Maidl (1987) Müller (1978) Lechnitz & Schrewe (1987) Kuhnenn (1995)
A2	Collapse of the unstable excavated front face incorporating a man-made feature such as old borehole, well or culvert.	Seoul #3	
A3	Collapse of partly completed lining as a result of excessive settlement or convergence.	Kriberg, Weltkugel, (Kehrenberg), Seoul #6 Seoul #7, São Paulo 93, Italy, Montemor #1	Lechnitz & Schrewe Kuhnenn
A4	Collapse of the bench in the longitudinal direction.	Kaiserau	Schrewe & Maidl Lechnitz & Schrewe
A5	Collapse of the bench during excavation in the direction to the centre of the tunnel.	Kaiserau, Lambach	Schrewe & Maidl Lechnitz & Schrewe Kuhnenn
A6	Longitudinal "cantilever" collapse of the heading in advance of the first section of completed ring.	Paris, Massenburg	Müller
A7	Collapse due to the crown excavation being too far in advance of the closure of the ring. [fig. 13]	Paris, Bochum #1 São Paulo 93	Kuhnenn
A8	Collapse due to failure of the temporary invert to the crown section. [fig. 7]	Landrücken	
A9	Collapse due to bearing failure under the "elephants' feet" to the crown section.	Bochum #1	Schrewe & Maidl Lechnitz & Schrewe Kuhnenn
A10	Collapse due to structural failure of the partial completed lining - for example due to local overstraining or rock joint movements.	Landrücken, Kriberg, Michaels	Schrewe & Maidl Müller Lechnitz & Schrewe Kuhnenn

Table 2 Reported cause of collapse (see figure 6) continued

CAUSE OF COLLAPSE		LOCATION	AUTHORS
A11	"Pause in work" collapses before ring completion.	Karawanken	Schrewe & Maidl Lechnitz & Schrewe Kuhnenn
A12	Collapses where the failure was in part due to an identifiable construction defects.	Munich #2, Munich #4, Munich #5, Munich #6	Schrewe & Maidl Lechnitz & Schrewe
B - in the area of the tunnel with the completed primary NATM lining			
B1	Collapse due to general excessive settlement or convergence.	Bochum #1	Kuhnenn
B2	Collapse due to more local overstressing usually as a result of unanticipated or unallowed for loading conditions.		Schrewe & Maidl Müller Kuhnenn
B3	Collapses largely as a result of substandard materials or significant construction defects.		Lechnitz & Schrewe Kuhnenn
B4	"Pause in work" collapses concerning the junctions of old and new parts of the NATM lining.		Schrewe & Maidl Lechnitz & Schrewe
B5	Collapses due to inexpertly undertaken repairs, changes or corrections to the profile of the NATM primary lining.		Schrewe & Maidl Lechnitz & Schrewe
C-Other collapse locations and mechanisms			
C1	Collapses at portals - usually associated with problems of weathered or loose rock or ground. [fig. 14]	Carvalho Pinto, (Funagata)	Schrewe & Maidl Lechnitz & Schrewe
C2	Collapses at break-outs from vertical construction shafts - usually associated with weak ground and/or water on the outside of the shaft construction. [fig. 9]	Munich #1	

54 The construction of tunnel portals (category C) is a hazardous part of any tunnel construction and is not unique to NATM construction. This hazard arises because the ground is able to move towards the open face from which the portal is being driven, and because the ground may have been affected by weathering. This additional degree of freedom significantly reduces the mobilisation of shear strength within the ground to support the tunnel. Most tunnel portals are sited in areas where the consequences of collapse are not likely to be high.

Causes given by others to explain NATM tunnel collapses.

55 Views are often expressed in the literature about the causes of the collapse. The views are those of authors, often academics and consultants, who are, in the main, supporters of NATM. They are included in this review of information and for what they reveal of the range of perceived incident causation. They do not represent the views of any official government regulatory investigators and caution

should be applied to their interpretation. Investigations into tunnel collapses are rarely able to point to one specific cause, and most failures reported are due to a combination of circumstances.

56 There is a tendency in the literature to blame either the ground or the workers or both, but rarely to look further and examine the NATM design, construction methods and the systems of work. For example in more than one instance a sudden deterioration of the ground conditions at the face has been claimed at the same time as a reduction in the quality of the support work at or near the face. Nowhere in the literature studied was there a conclusion that the choice of the tunnelling system (i.e. NATM) was wrong in the circumstances of the site.

57 For the purposes of this review these causes have been collated into five broad categories;

- unpredicted geological causes;
- planning and specification mistakes;
- calculation or numerical mistakes;
- construction mistakes; and
- management and control mistakes.

1 Unpredicted geological causes

Notwithstanding ground investigations prior to construction, the most common unpredicted geological feature leading to a collapse is the occurrence of washout or erosion structures in the ground. This is often due to unsuspected lenses of water bearing sand or gravel, often just outside the tunnel profile. It is usually good practice to continue the ground investigation, particularly through forward probing, during the construction process and for the need for competent persons to examine and record the excavation face(s).

'Unpredicted' ground conditions, which is not the same as 'unpredictable', are frequently reported as the cause of collapses.

2 Planning and specification mistakes

Tunnel failures have occurred due to failure at the planning stage to locate underground structures such as wells, culverts and unfilled or poorly filled boreholes. These are not dissimilar to unpredicted geological features.

Other planning and specification mistakes reported include:

- tunnel level too high; inadequate competent ground cover to the tunnel;
- excavation and support measures specified without regard to the geological features;
- faulty ground classification system leading to inappropriate support;
- inadequate specification of construction materials;
- inadequate specification of tolerances on profiles or levels;
- inadequate specification of lining repair procedures; and
- inadequate planning for the unexpected or for emergency measures.

3 Calculation or numerical mistakes

Calculation and numerical mistakes arise both during design and construction, the latter frequently in connection with the monitoring data. Other reported mistakes include:

- adoption of incorrect design calculation parameters;
- insufficient allowance for the effect of water;
- use of inappropriate and/or invalidated computer programs;
- numerical mistakes in gathering tunnel monitoring data; and
- failure to process numerical monitoring data fast enough.

4 Construction mistakes

A wide range of construction errors, too numerous to tabulate in full, have been recorded covering almost all aspects of the construction work. Some of the most common are:

- lining not constructed to specified thickness;
- faulty installation of rock anchors and lattice arches;
- faulty installation of ground freezing pipes;
- incorporation of excavated material, and rebound in the invert concrete;
- poor profiling of the invert; and
- badly executed lining repairs.

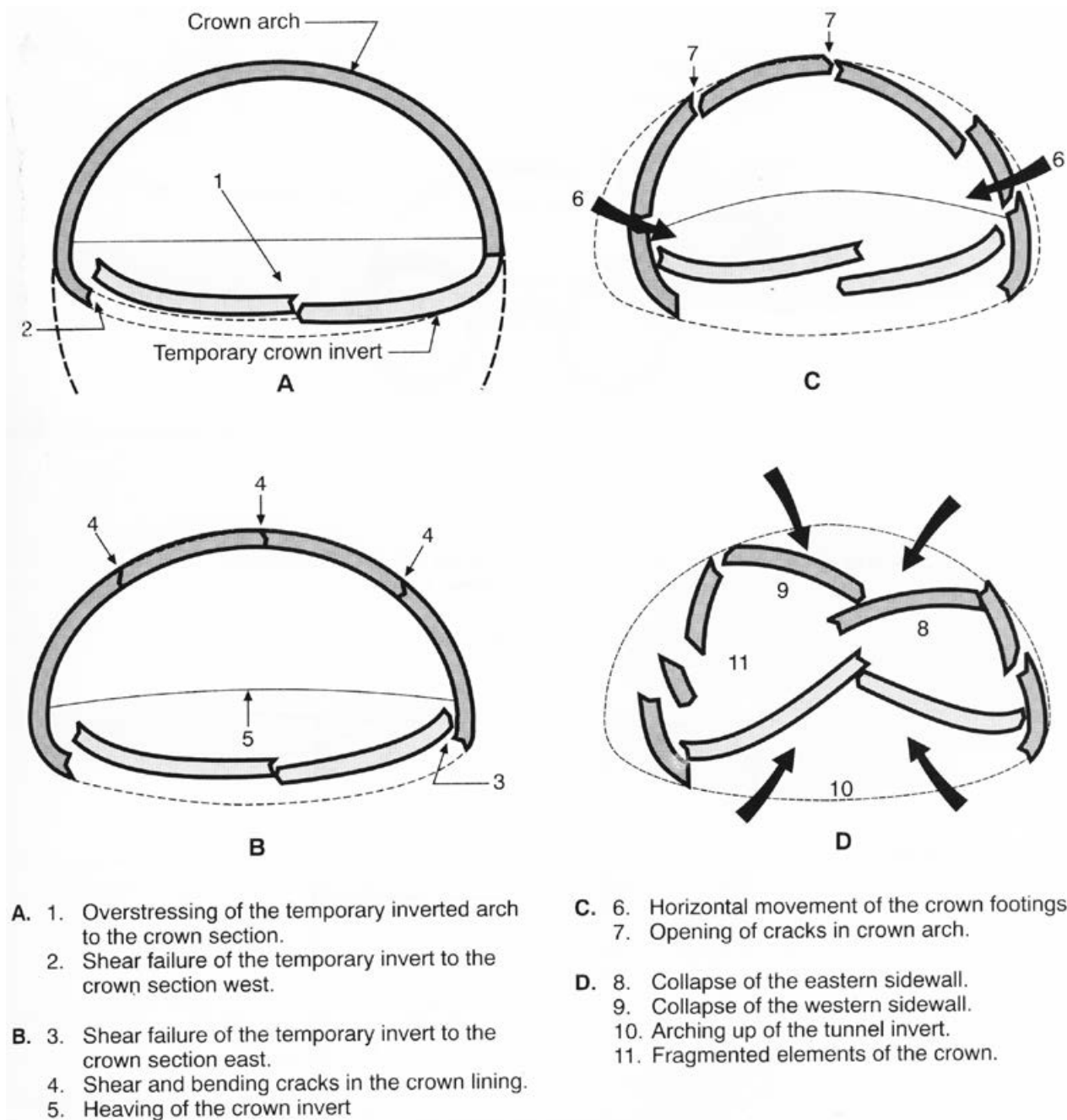


Figure 7 Table 1(4) Incident at Landrucken tunnel, Germany
(after John, Wogan and Heissel, 1987)

5 Management and control mistakes

Management and control mistakes cited in the literature as leading to the collapse of NATM tunnels include:

- retention of incompetent or inexperienced NATM designers;
- incompetent or inexperienced site management.
- management's inability to learn from past experience, both good and bad;
- retention of incompetent or inexperienced construction contractors;
- poor supervision of construction work;
- allowing the wrong sequence of tunnel construction in multi-tunnel situations;
- failure to act on monitoring data.

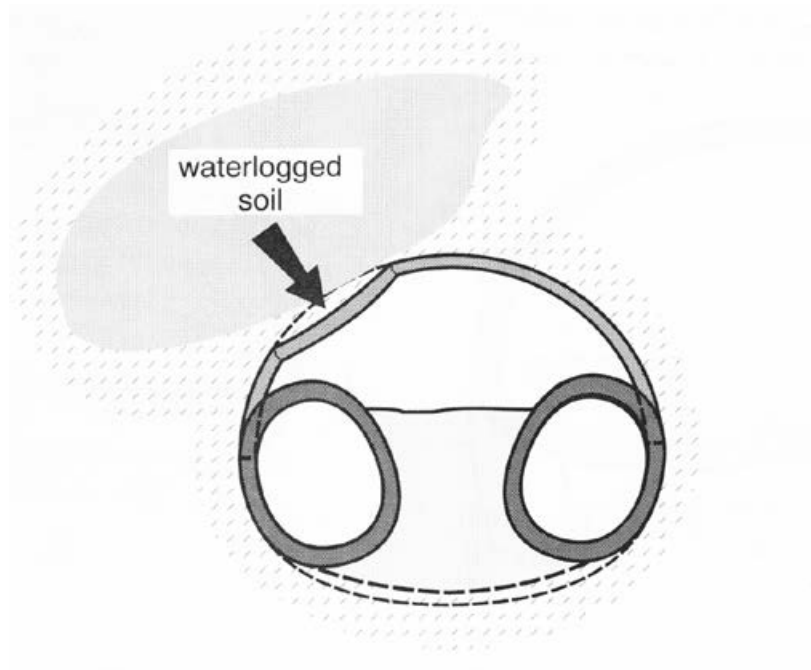


Figure 8 Table 1(9) Incident at Krieburg tunnel, Germany (after Lechnitz and Schlitt, 1987)

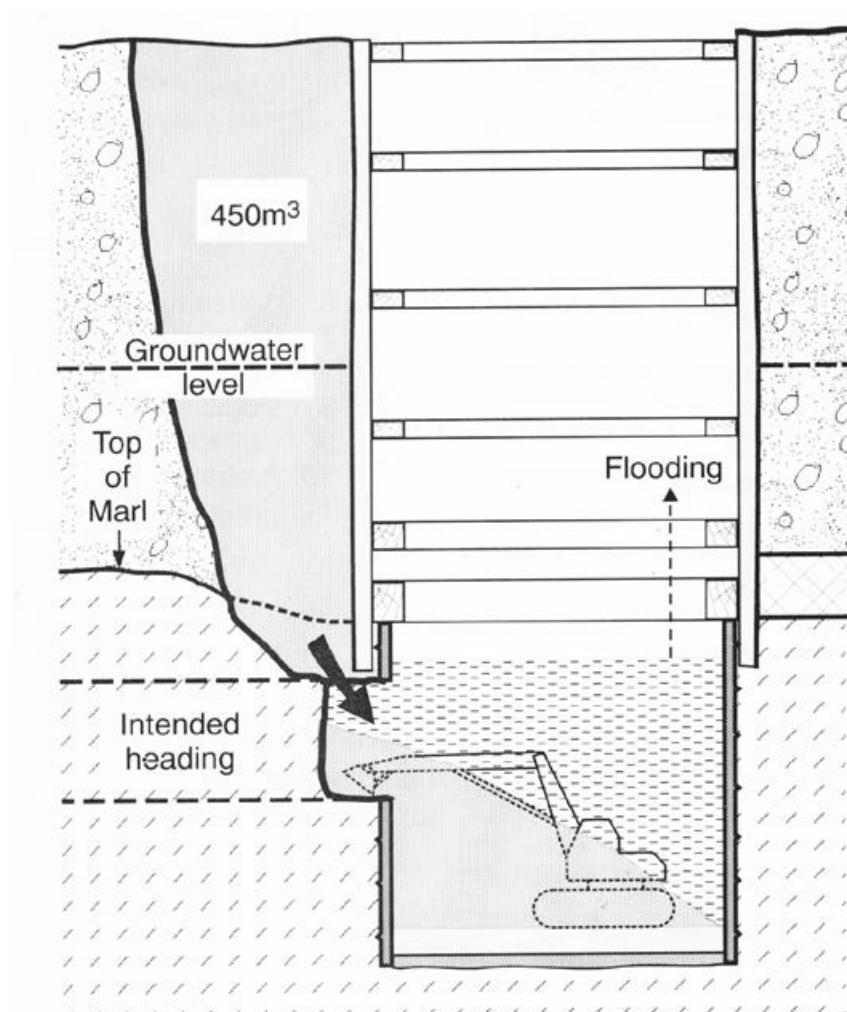


Figure 9 Table 1(10) Incident at Munich, Germany (after Weber, 1987)

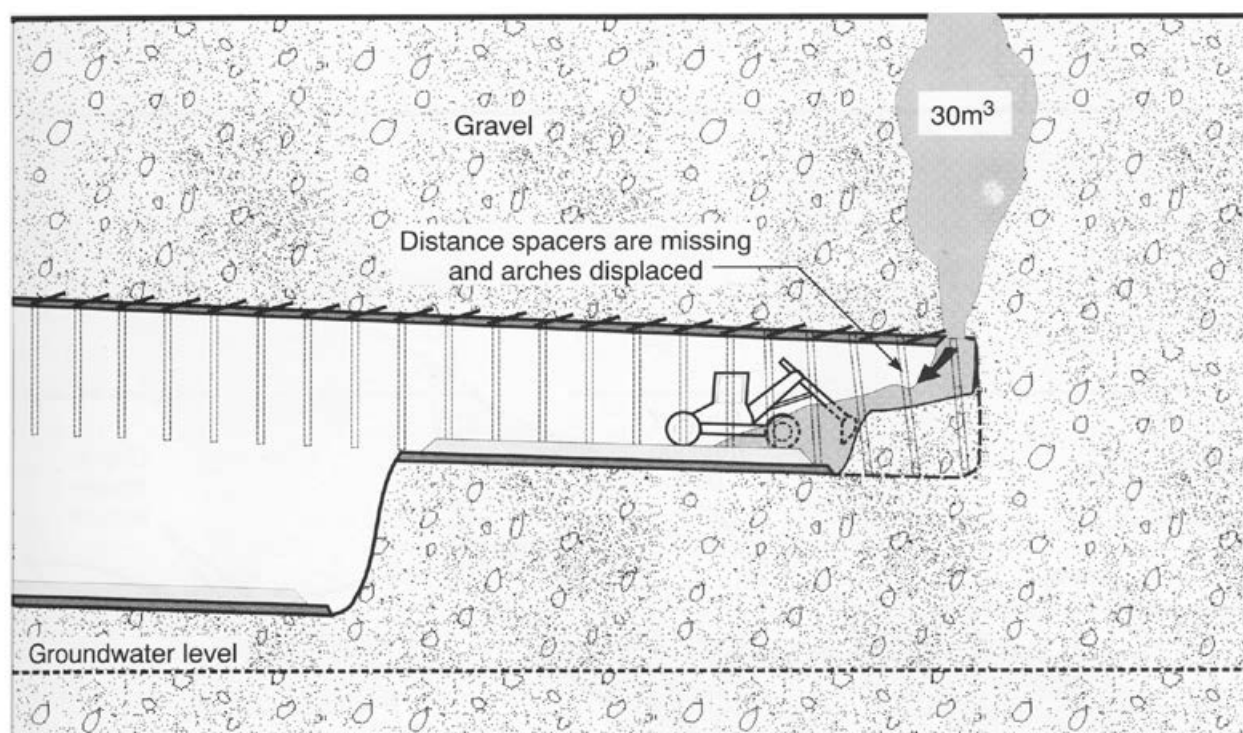


Figure 10 Table 1(11) Incident at Munich, Germany (after Weber, 1987)

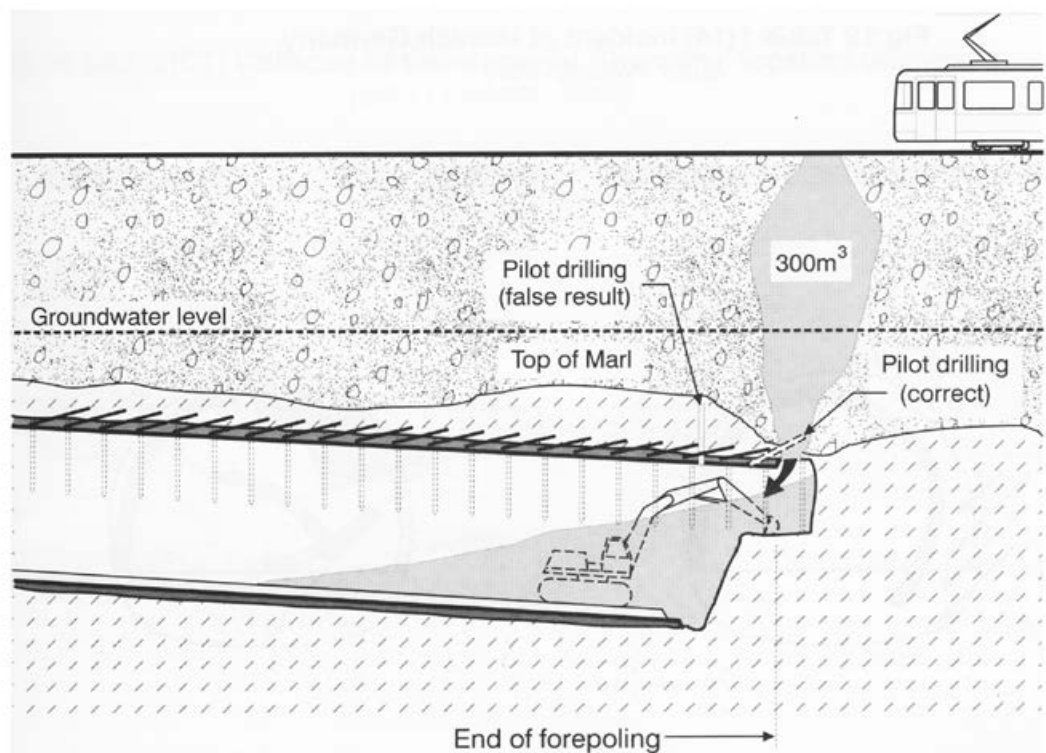


Figure 11 Table 1(12) Incident at Munich, Germany (after Weber, 1987)

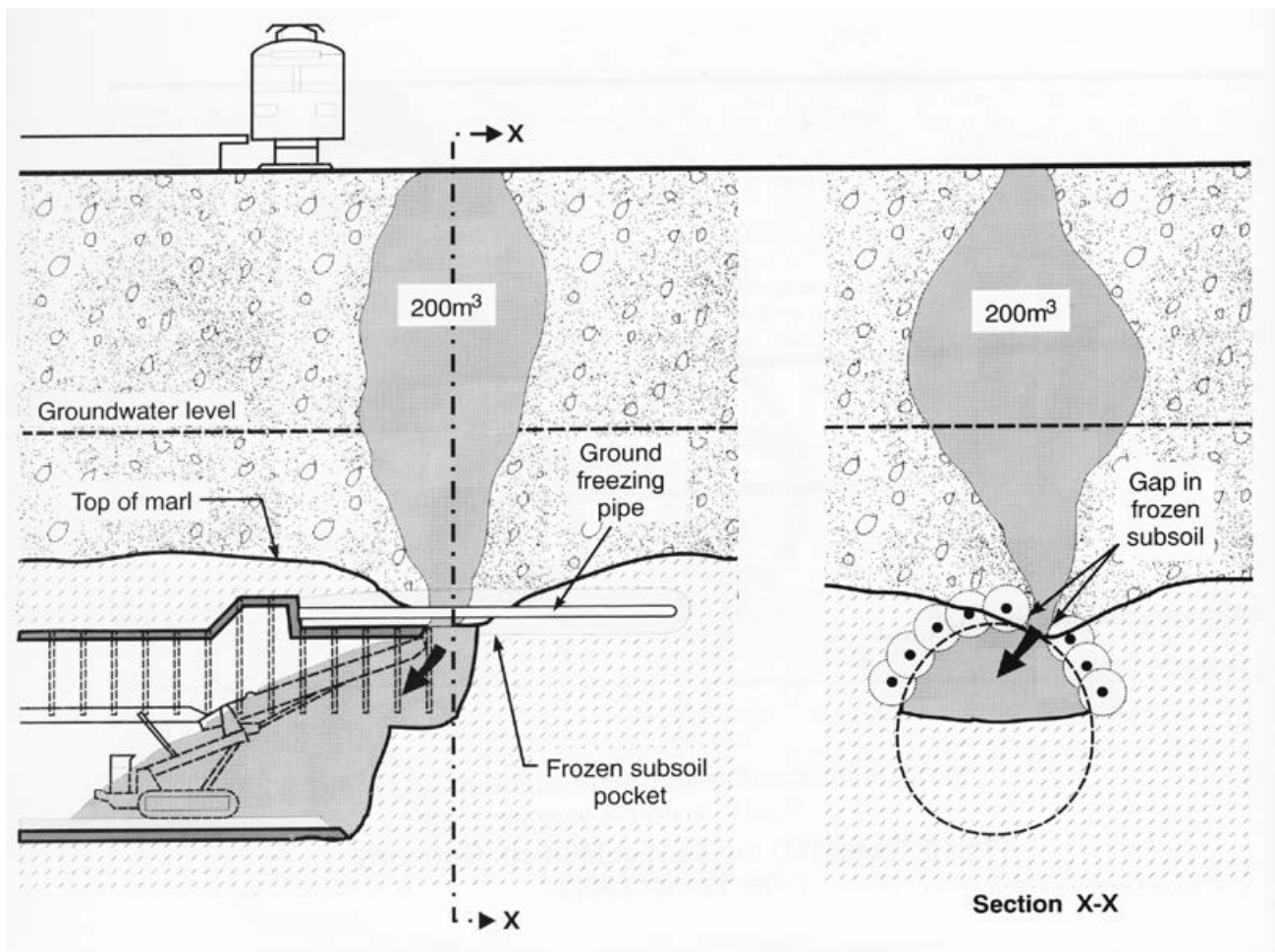


Figure 12 Table 1(12) Incident at Munich, Germany (after Weber, 1987)

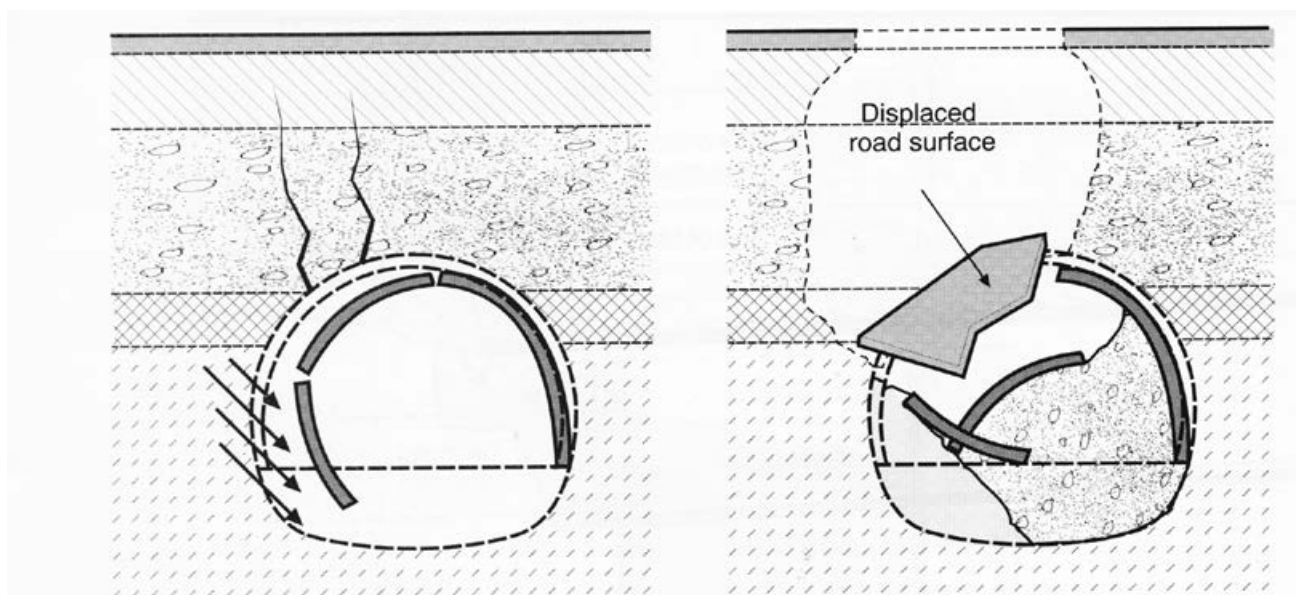


Figure 13 Table 2(A7) Collapse due to excavation being too far in advance of the ring enclosure Subway tunnel in Germany (after Müller, 1978)

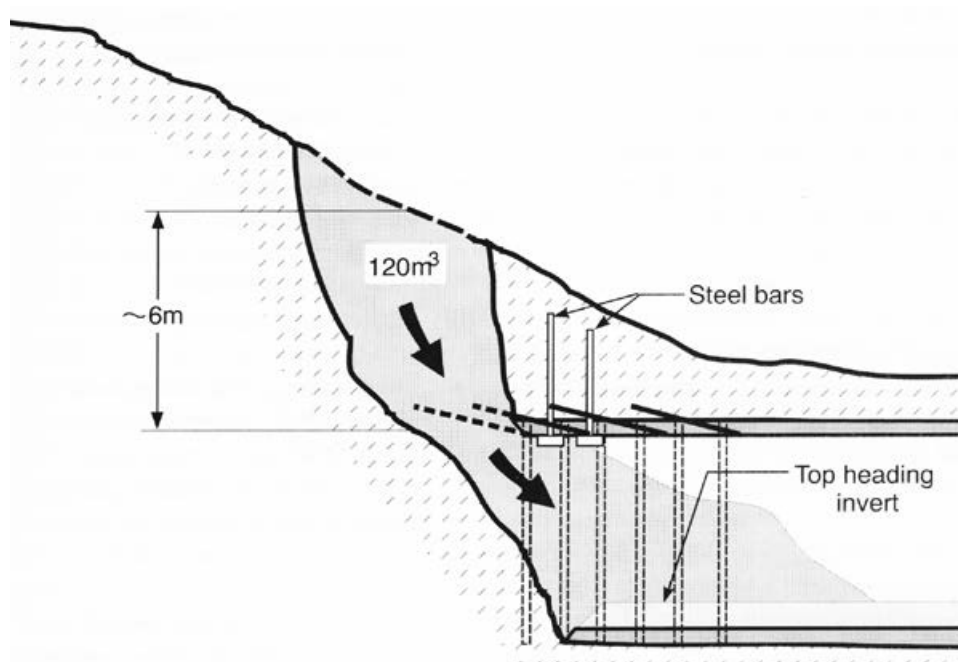


Figure 14 Table 2(C1) Collapse of tunnel portal (Germany, location unknown) (after Lechnitz, 1990)

Remedies suggested by others to avoid NATM collapses

58 The literature suggests various remedial measures which could have prevented the collapses described. These measures whilst obviously specific to the circumstances of the collapse and to the site, have been collated and are listed below for information.

(i) Construction improvements:

- include 'dumplings' to give temporary support to the excavated face;
- change the tunnel excavation sequence to include more partial faces, i.e. by employing side drifts in the tunnel excavation to be driven prior to the full cross-section;

- widen the bases of the crown arch supports (elephant's feet);
- add base anchors to the crown arch support detail;
- add spiling and/or forepoling to reinforce the ground above the crown;
- undertake drainage of the ground in advance of the tunnel construction (for example by dewatering wells, or by the construction of a pilot drainage tunnel);
- chemically grout the ground in advance of the tunnel construction;
- add a curved (temporary) structural invert to the crown section;
- thicken the lining;
- construct shorter 'pulls' at the face;
- increase the curvature of the invert of the lining;
- add reinforcement arches all round the whole tunnel cross-section even when not strictly essential;
- use low pressure compressed air (but consider other health and safety implications).

(ii) Management improvements:

- use competent staff to examine closely the excavated face during construction to minimise geological risks;
- implement a properly considered policy on ground and rock sampling;
- pass the results of geotechnical measurements to experts for their immediate interpretation;
- pay strict attention to construction quality;
- ensure careful pre-planning of construction activities;
- pay special attention to control measures when work resumes after a site shut down;
- work in closer teams (client/contractor);
- introduce a positive safety culture.

(iii) Other suggested improvements:

- use an appropriate soil/ground/rock classification system to help define the NATM support measures, along a tunnel of variable geology;
- install better monitored sections of the tunnel at or near critical structural areas;
- test the mass rock and ground properties with care before using the values obtained in any stability and strain calculation processes;
- undertake realistic stress analysis;
- lower the tunnel to increase the depth of competent overburden;
- use trial headings.

Discussion

59 Excluding the portal incidents, nearly all reported NATM tunnel collapse incidents originate within the tunnel heading (figure 6). Therefore, the inherent problem with NATM tunnel construction appears to rest in the construction of a heading. Safe construction of a heading requires that the excavated face, and the short length of incomplete lining immediately next to it, is stable and under control at all times. The frequency of reported incidents, where this has not been achieved, is high and it is probable that many more unreported and other minor incidents have occurred.

60 Alternative forms of tunnel heading construction, for example a closed face tunnel shield or tunnel boring machine, can provide emergency ground support that limits the movement of ground into the heading. This can limit the risk of development of a hole above the tunnel and thereby reduce the surface hazard. Open faced excavation techniques are not unique to NATM tunnels, and they are a hazard in all forms of tunnel construction.

61 A particular hazard of NATM is the absence of any ready means of supporting the heading should ground collapse into the tunnel. Ground may then move into the heading and a crown hole develop above the tunnel. If the tunnel is shallow, and especially if the ground is water logged, a crater-like depression may form in the ground surface. In urban areas this may result in a high consequence event. For larger diameter tunnels, commonly constructed using NATM, the consequences which arise, predominately from the excavation and immediate ground support processes, may be further exacerbated.

62 Table 2 summarises the reported causes of collapse within tunnel headings. The cause most frequently cited for the heading collapse is unstable ground conditions. Obviously, if a more appropriate construction method had been selected the tunnel heading would not have collapsed. Hence the cause of the collapse is not the ground but the use of the wrong construction method in the ground conditions which existed. This kind of error can only occur if those responsible for the construction:

- had not foreseen deficiencies in the construction method in use in the ground conditions encountered;
- had not foreseen changes in the ground conditions and hence did not alter the construction method in time;
- failed to identify the nature, and hence predict the behaviour, of the ground encountered.

63 Typically, heading failures in shallow tunnels occur when permeable water bearing ground is close to the tunnel. The presence of water appears to be critical. If it is not present the loose ground falling into the heading will form a fairly steep stable slope. This slope will block the tunnel and thereby limit the size of the 'crown' hole above the tunnel. In the presence of water, this type of heading failure occurs fairly rapidly. And it is likely to be too fast for emergency support to be erected within the NATM tunnel especially as work close to the collapsing heading is unsafe. For emergency support to be effective it is probably necessary for it to be designed so that it can be partly erected, and kept ready for immediate use close to the heading.

64 In most of the reported major tunnel heading collapses the rate of development, though rapid when compared to the time to erect emergency heading support, has not been fast enough to trap the miners. The main risk to the miners comes from relatively small falls of ground within the heading, typically blocks of ground falling from an otherwise stable face. The types of injury caused by 'block' falls are recorded in the literature but insufficient detail is available about the precise causes. Therefore it is not known how many are due to falls of ground as opposed to falls of construction equipment and materials. In London, during the period in which this review was being prepared, there has been at least one serious injury to a miner caused by a fall of ground in a tunnel heading. The technical literature on tunnelling in London reports fatalities due to people being struck by 'block' falls of London clay (Harding 1981).

65 Reports of NATM tunnel heading collapses often mention consequent delay in completing the project. When considering whether to adopt open-face excavation techniques, such as NATM, the consequences of a significant heading collapse should be taken into account. The need for significant expenditure on emergency support measures, necessary for the purposes of health and safety, should also be considered.

66 It is clear from the references given in table 2 that NATM lining failures do occur but they are not well publicised, and they tend to be poorly documented. As a result many of the incidents alluded to in table 2 do not appear in the list of

Table 3.1 Failure mechanisms: Ground collapse in heading

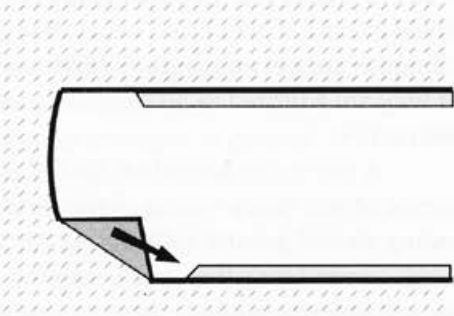
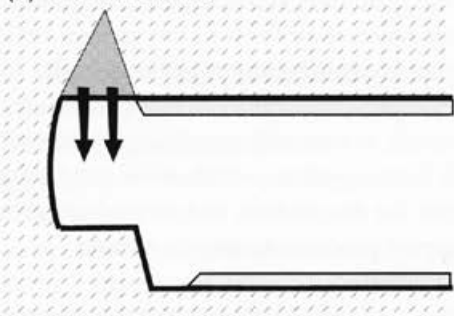
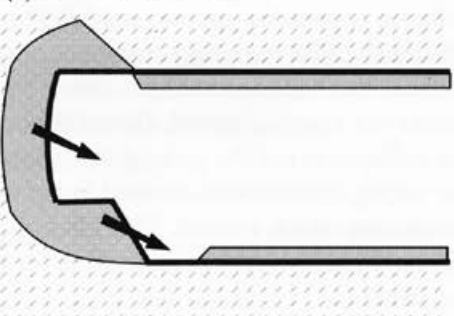
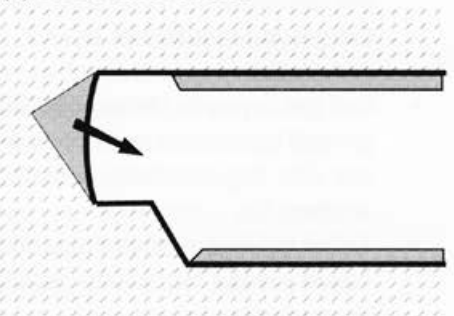
Number	Type of failure	Illustration of failure
(i)	Heading in ground too weak for method May be due to discrete zones of weakness (discontinuities) including "greasy backs" Bench failures may be transverse or longitudinal	(a) Bench failures 
		(b) Crown failures 
		(c) Full face failures 
		(d) Local face failures 

Table 3.1 Failure mechanisms: Ground collapse in heading continued

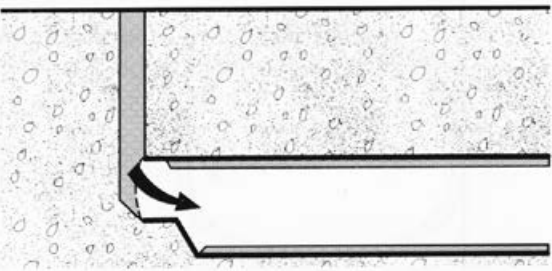
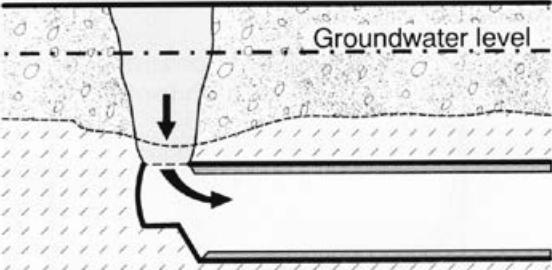
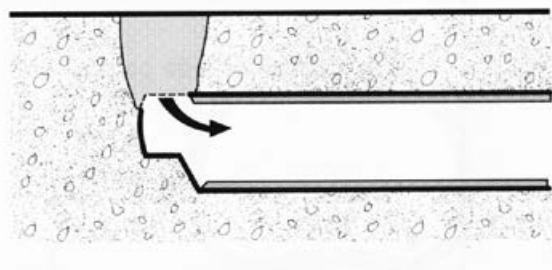
Number	Type of failure	Illustration of failure
(ii)	Weakness in crown Due to vertical fissures, pipes and man made features (wells, etc.)	
(iii)	Insufficient cover to overlying permeable water bearing strata	
(iv)	Insufficient cover to surface	

Table 3.2 Failure mechanisms: Failure of lining before ring closure

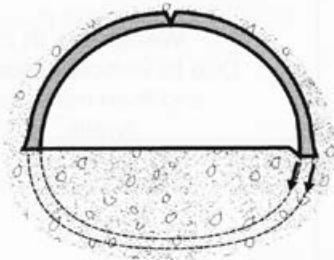
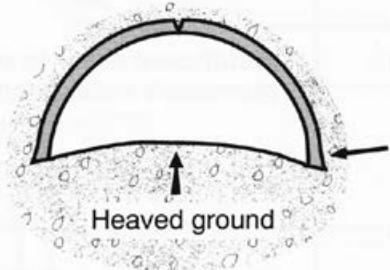
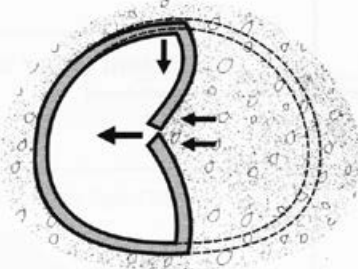
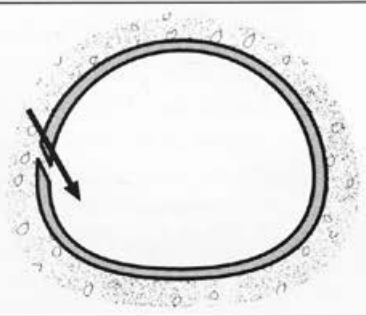
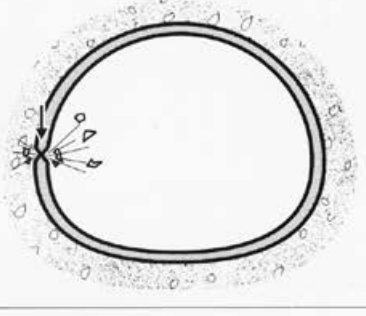
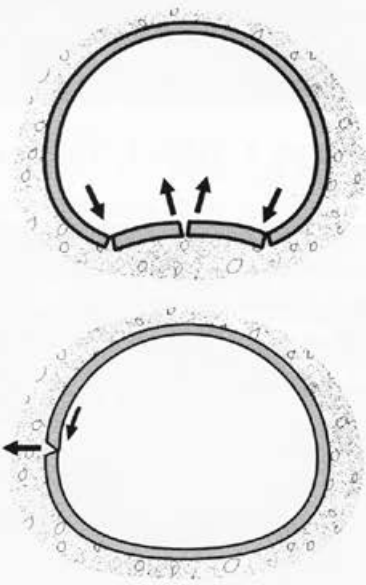
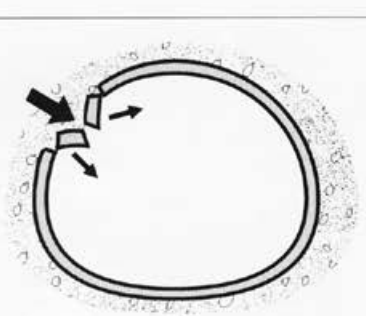
Number	Type of failure	Illustration of failure
(i)	Bearing failure of arch footings (Typically enlarged footings "Elephant's feet")	
(ii)	Failure due to horizontal movement of arch footing	
(iii)	Failure of side gallery wall	

Table 3.3 Failure mechanisms: Failure of lining before or after ring closure

Number	Type of failure	Illustration of failure (after ring closure)
(i)	Shear failure	
(ii)	Compression failure	
(iii)	Combined bending and thrust	
(iv)	Punching failure	

collapses described in table 1. This imbalance in reporting makes it difficult to establish the overall level of risk, and as a result the risk of lining failure may be underestimated.

67 HSE has analysed causes of collapse and has identified a number of generalised collapse mechanisms applicable to NATM tunnels in London clay. These are set out in table 3. These are grouped into three categories:

- ground collapse in the heading;
- failure of the lining before ring closure;
- failure of the lining both before and after ring closure.

These mechanisms may provide a starting point for project specific analysis.

2.3 Consequences of collapse

68 The world-wide data show that NATM tunnels, especially built in soft ground in urban areas, may, when they collapse, result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment. Four examples are described below.

Kwachon, Korea

69 Photo 1 shows the collapse of the 14th section of a NATM tunnel of the Kwachon Subway, Korea. (table 1 no. 21) A newspaper report indicates that “the construction company revealed that the large scale collapse occurred as the clays which had been trapped between the soil and the weathered rock were washed away by rain. The supports within the tunnel gave way.” Four workers were trapped but successfully rescued unhurt 26 hours later.



Photograph 1
Table 1, Number 21
Collapse of Kwachon
tunnel, Korea 1991

Seoul, Korea

70 Photo 2 shows the aftermath of the collapse in 1991 of a NATM tunnel which was part of the second phase of the Seoul Metro. (table 1 no. 23). The excavated face in ‘weathered rock’ collapsed into the tunnel resulting in a crater at street level. The face collapse was described (Park and Lee 1993) as a “sliding or wedge failure” with the bedding planes of weathered rock being almost parallel to the

tunnel axis, where there was a high probability of the rock sliding down along joint planes. There was 3m rock cover and a total overburden depth of 28m. Following the collapse a 100mm pressurised water main burst; an 800mm sewer pipeline was broken; power cables were severed; and gas mains damaged.



Photograph 2
Table 1, Number 23
Collapse of Seoul Metro
tunnel, Korea 1991

Sao Paulo, Brazil

71 Photo. 3 shows the after-effects of a collapse in a NATM tunnel under construction beneath the Avienda Santo Amaro in Sao Paulo, Brazil in November 1993 (table 1 no. 32). One newspaper report refers to an official report which was commissioned from the USP Technological Research Institute aided by a commission of specialists but this document has not been obtained. It is understood that the NATM tunnel was being constructed in soft ground using the crown and bench excavation method and that the overburden was decreasing as



Photograph 3
Table 1, Number 32
Tunnel collapse in
Sao Paulo, Brazil 1993

the tunnel level was rising to meet a cut and cover section. The construction system involved the placing of a temporary invert to the crown following crown excavation. The distance between the temporary inverted arch and the excavation face in the area of decreasing overburden was critical to the safety of the heading. This distance was not as intended and the level of safety was reduced which resulted in critical vertical displacements in the crown arch. There was a rupture of the face followed by the failure of a culvert containing the Sapateiro stream and a water main both located above the tunnel. Water flooded into the collapsed tunnel and a crater of some 20m in diameter was formed at the street level.

Principal conclusion

NATM tunnel collapses in urban areas can result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.

Munich

72 On 20 September 1994 a collapse occurred during the construction of a NATM tunnel drive on the Munich Trudering underground railway line (photo. 4; table 1 no. 38). No official report has been published and the following circumstances of the collapse are taken from newspaper reports and news articles. (Spaun 1995).



Photograph 4
Table 1, Number 38
Tunnel collapse in
Munich, Germany 1994

73 The location of the collapse was some 25m from the access shaft and there was some 17m of cover above the top of the tunnel. The excavation was in clay/marl, and it was anticipated that there was 1.5m to 2m of this impervious material above the tunnel construction. Above this level up to the underside of the road construction there were waterlogged gravels – the ground water level being about 2.5m below the road surface. It appears that water penetrated the tunnel construction at the face, and increasingly large quantities of gravel and water entered the tunnel. The tunnel was evacuated and on reaching the surface a miner urged the driver of a bus to drive away because of the risk of surface collapse. However before the bus could move the road surface collapsed and the bus slipped backwards into the surface crater which was partially filled with water. Several bus passengers were drowned and others injured. Tragically the miner also fell in to the crater and was killed.

2.4 Analysis of accident data

74 Although table 1 shows that many NATM collapses result in major consequences, experience elsewhere suggests that for every major collapse there are likely to be many more lesser incidents. There is very little information in the literature about such events, but it is known that fatal accidents occurred at Galgenburg (1994) and Munich (1994). In addition Waninger (1982) reports on the investigation of 32 collapses in Germany between 1976 and 1982. Two of these involved fatal accidents, 12 involved unspecified injuries, and 20 collapses caused no injuries to personnel. There are no published data for the UK comparing the accident record of NATM compared with other tunnelling methods. HSE has seen a report which indicated that for one event involving collapse of material from the tunnel face which caused injury, 14 other non-injury events had previously occurred. And HSE has seen a small study, undertaken on one project, which compares the accident frequency and severity between the NATM and non-NATM tunnelling work, and suggests that they are broadly comparable. However as the work is not yet completed no firm conclusions can be drawn.

2.5 Recent NATM work in the UK

75 Following the NATM tunnel collapse at Heathrow all those undertaking such tunnelling projects in the UK agreed voluntarily to suspend NATM until they could demonstrate to HSE their ability to work safely.

76 HSE has since scrutinised over 30 NATM proposals, ranging from small-scale to substantial works. Except for the smallest and simplest jobs HSE found there were, at the outset, significant deficiencies in the proposals. Some technical aspects of NATM design and construction were poorly understood, in particular the heading stability including both the excavated face and the incomplete lining, and the possible effects of compensation grouting.

77 Each project had the benefit of NATM advisers of international standing to assist them and it may therefore be reasonable to conclude that the deficiencies noted fairly reflect the international state of NATM tunnel design and construction. HSE found that, given the goodwill and efforts made by the parties involved, during the process of considering the restart proposals coupled with on-site verification, it was possible satisfactorily to resolve the issues which arose. HSE also noted that later submissions began to show a marked improvement.

78 The following list sets out the significant general issues which arose, both from the documents submitted to HSE and from on-site verification by HSE, as work proceeded. It does not list matters specific to any one project. And it should be stressed that the list represents cumulative experience. It should not be taken to imply that any of the deficiencies listed were found in all proposals.

Principal conclusion

Provided careful account is taken of all the issues in this review, it has provided possible for NATM work to proceed in safety

Legislation

- Failure to consider the legal implications of delegating work to others whilst retaining legal duties of care especially for third parties.
- Little understanding of the significance of the hierarchy of risk and risk control in the MHSWR Approved code of practice. (For explanation of the terms CDM and MHSWR see part 3 and appendix 4).

Hazard and risk

- No concept that tunnel construction in urban areas can have potential consequences of failure similar to those which might arise from a major hazard activity.
- Poor understanding of how to undertake a risk assessment and of the concepts of hazard and risk.
- Failure to consider all possible collapse mechanisms of the tunnel heading and completed tunnel primary lining.
- Inadequate appreciation of the likelihood of failure.
- Inadequate analysis of hazards e.g. hazards from utilities in the event of settlement or collapse not considered.
- Inadequate consideration of potential consequences of failure resulting in a major event.
- Inability to turn the risk assessment into effective risk control and risk management measures.
- Limited appreciation of what level of residual risk could be considered tolerable.
- Failure to consider how to 'discover' emerging trends and ensure that 'recovery' through remedial action can be taken within the time available.
- No sensitivity analysis to enable the relative importance of differing risks to be judged.

Management Policy

- Clear policies not set up so that everyone on the project knows what standards are expected.
- Lack of appreciation of possible high consequence events resulting in a failure to address the implications of this for the organisation.
- Failure to have in place satisfactory quality assurance procedures especially during construction.
- Accident and incident data not systematically collected and evaluated.

Organisation Control

- Inadequate, or non existent challenge functions built in to review safety critical issues.
- Control systems not independent of those with a vested interest in the outcome.
- Failure to set up adequate quality assurance systems not just linked to construction quality but to the full process including design.
- Staffing levels to ensure continued integrity of risk control measures not considered.

Co-operation

- Failure to set up reporting and supervisory systems at an appropriate management level.
- Arrangements for inter-organisation and intra-organisation communication not clear; implications for decision making not clear.

Communication

- Failure to put in place effective management information systems to ensure decisions are made at an appropriate management level.
- Common-mode failures within management hierarchy not considered.

Competence

- Failure to establish appropriate levels of key competencies and undertake a training needs analysis to establish whether a sufficient number of competent people are available and deployed as needed.

Planning and implementation

- Inadequate geometrical planning in relation to the scheme of tunnelling to be used (i.e. buildability).
- Possibility of failure not acknowledged and hence not planned for nor considered in management systems.
- Failure to consider human factors, and issues of safety culture especially with respect to management systems, human reliability, the physical and the non-physical working environment.

Measuring performance

- Inadequate arrangements to review monitoring data and reach appropriate decisions.
- No pro-active management system for the use of geological data obtained from face logging and forward probing.

Procurement

- Inability to justify in health and safety terms why NATM was selected.
- Ill-considered separation of temporary and permanent works design.
- Inadequate co-ordination of potentially incompatible technologies (e.g. compensation grouting with NATM tunnel construction).
- Failure to specify contractor requirements to deliver safety through design, quality control, monitoring, and contingency and emergency plans.
- Failure adequately to check the competence of designers.

Design

- Inability to explain design rationale.
- Failure adequately to consider buildability – such as invert joints, side wall drift joints, break out sequence for enlargement.
- Failure adequately to design face support measures.
- Failure to set appropriate design criteria for temporary works, such as safety factors.
- No explanation of design elements particularly sensitive to variations in construction.
- Inability to produce design drawings or other details at all for many aspects of the proposed construction works.

- Effects of settlement on services and other sub-surface structures not adequately considered.
- Design focused solely on final integrity of the structure. 'Category 3 design checks' done which did not consider intermediate stages of construction. Yet these checks were presented as being indicative that the design could be safely built.
- Information supporting the design insufficient to enable the work to be undertaken safely.
- Inadequate understanding of the nature of London clay.
- Use of unvalidated computer programs for the analysis of the lining/ground interaction and lining design.
- Use of incorrect constitutive soil models in the analysis of the lining/ground interaction.
- Lack of detailed ground investigation to find out the strength and discontinuities within the ground and failure to carry out the necessary stability assessments of the tunnel heading.
- Failure to use all known ground information e.g. results of the pilot or trial tunnel and prior construction experience.
- No consideration of empirical data on the deformation of the linings in London clay.
- No consideration of lining failure modes and associated tunnel collapse mechanisms.
- Use of inappropriate factors of safety in the design of sprayed concrete linings.
- Inadequate consideration of safety critical concrete failure modes, especially failure in bending and proportioning (including reinforcement details) required to ensure 'ductile' failure.
- Inadequate consideration of the timescale over which failure could occur.
- Poor detailing of construction joints.
- Inability to justify choice of excavation sequence on a rational basis e.g. use of side wall.
- Interactions between other tunnel structures etc. in close proximity not adequately understood.
- Failure to assess numerically the stability of the incomplete sprayed concrete lining within the tunnel heading.

Monitoring

- The objectives or purpose of monitoring the lining not clear.
- No concept of the need for safety monitoring; monitoring limited to checking that design assumptions are reasonable.
- Failure to set criteria against which to monitor.
- No methodical monitoring of the heading and especially the face stability.
- Poor geological monitoring of the excavated face and probing ahead.
- No proper identification of lining failure mechanisms and hence poor definition of the allowable deformation of the lining, trigger values, etc.
- Trigger levels and trend rates not considered, or when considered were incorrectly set.
- Poor appreciation that rate of change, and trend data even within the established trigger levels should be considered and reviewed.
- Use of pressure cells to confirm design assumptions despite stating that such instruments are generally regarded as unreliable.
- Use of single pressure cell in a shotcrete section subject to uneven loading caused by bending, when the reading could not be interpreted as the position of the neutral axis was not known.
- Lining deformations monitored using absolute position surveying techniques, which are not accurate enough to detect all critical movements in a sprayed concrete lining, instead of well established invar tape extensometers.
- Failure to review trigger levels and trend values on the basis of back analysis of emerging monitoring data.

Construction

- Failure to properly plan the construction methods to be used within the tunnel heading and hence a reliance on *ad hoc* methods of construction.
- An over-reliance on observation during construction to avoid tunnel collapse without adequate design and planning.
- Failure to support excavated face and protect miners from 'block' falls even though this cause of failure was well known in London clay prior to current construction projects.
- No consideration of heading support techniques and resulting strains within the ground leading to increased surface settlement and weakening of ground support to the tunnel.
- Failure to integrate face support and other NATM construction issues.
- Either no or inadequate quality control on strength of concrete at critical locations such as the invert.
- Inadequately worked-out method statements resulting in impractical procedures and construction methods being proposed which would then have to be changed during construction.
- Assumption that everything would be right first time and no thought given to planning and procedures needed to deal with construction deficiencies.
- Failure to ensure correct thickness of lining.
- Failure to ensure correct profile of lining including bulges in the sides and flattened or cusped inverts which could result in excessive bending stresses in the lining and provide potential failure points.
- Failure to maintain adequate alignment of lining across construction joints.
- Voids behind reinforcement and arches/ribs.
- Inclusions of rebound material resulting in lamination and structural weaknesses in the lining.
- Failure to ensure adequate continuity of steel and overlap of reinforcing mesh.
- Failure to interpret and act upon evidence of poor quality identified from test samples/cores.

Compensation Grouting

- Use of compensation grouting without quantifying its possible effects on the tunnel, both the completed lining and heading stability.
- Failure to control accuracy of horizontal drilling for tubes-a-manchette (TAMs) resulting in some being within or very close to the tunnel profile.
- Inadequate consideration of the additional loading on a recently completed lining caused by grout-induced deformations.
- No consideration of potential grout-induced pore water pressure increases at, near or in the tunnel face leading to reduced stability of the heading.
- Inadequate analysis of the stress and strain fields induced by grout injections and the potential effects on movement of adjacent structures and utilities, and additional long term consolidation.
- Inaccurate estimation of the ground surface movement occurring during a grouting trial.

Emergency arrangements

- Failure to adequately plan for contingencies and emergencies and to protect those at risk.
- Emergency plans inadequate to deal with major collapse.
- No plan of action in the event of trend rates or trigger levels being exceeded.
- No arrangements made for emergency support of the tunnel lining.
- Emergency plans not commensurate with the identified risks.
- Plans limited to the tunnel with no consideration of surface and public risk issues.

Principal conclusion

Major NATM collapses have occurred world-wide. This finding and recent scrutiny of proposals for NATM in the UK leads HSE to conclude that some safety critical aspects of NATM design and construction have been poorly understood, and past experience has not been adequately taken into account.

2.6 Comments

79 NATM tunnels require the deployment of considerable skill and care in their investigation, planning, design, construction and monitoring if they are to be safely constructed. HSE has found that the majority of the skills required are not unique to NATM though they may have to be applied in the particularly arduous conditions found in a tunnel. One such condition is the relatively short time in which the tunnel face and adjacent lining remains stable without support. The construction of the initial ground support must be carried out properly within a time which is unlikely to allow for the correction of significant errors.

80 Several of the NATM tunnel collapses described above appear to be due to a failure properly to plan and design for uncertainties, in particular for an unfavourable change in ground conditions. Procedures can be developed to overcome these uncertainties and permit safe NATM tunnel construction, but their successful application requires the proper management of complex technical issues.

81 After assessing the recent proposals for NATM construction in London, HSE has established that there is no intrinsic reason, provided careful account is taken of the advice contained in this review, why NATM work should not proceed in safety.

82 However, the list of deficiencies noted by HSE reflects many of the matters previously reported in the literature which lead to failures. HSE is seriously concerned that those, and their NATM advisers, introducing this technique into potentially high risk locations, seem not to have adequately taken account of past experience.

83 If further NATM projects involving new teams of clients, designers and construction contractors are to proceed safely all those involved should be in no doubt of the complexity of the task they face. To be certain that they have achieved an appropriate level of safety, both for their own employees and the public, they should undertake a rigorous and critical examination of the design and construction proposals before construction starts.

84 Difficulties experienced with NATM may have come about through unfamiliarity with the engineering technology. Comparable difficulties have arisen and have been successfully resolved by the construction industry before. Examples are the design of box girder bridges (Merrison, 1971) and a number of major falsework collapses some 20 years ago (Bragg, 1976). Lessons learnt were codified and disseminated; a growing reservoir of experienced designers and constructors was created. Provided that the current experiences from NATM are treated as recommended by this review, there should be an increasing confidence in future NATM projects.

85 Having reviewed past practice, parts 4, 5 and 6 give guidance on the main safety related issues.

Principal conclusion

NATM projects do not require skills not already available to the UK construction industry.

2.7 Safety of completed NATM tunnels

86 The UK has no long term experience concerning the safety of the public using tunnels constructed by the NATM. A world-wide literature search has identified one tunnel where safety problems developed after a NATM tunnel had been completed and taken into public use; and one where the point is uncertain.

87 The Carvalho Pinto Road Tunnel, Brazil was closed in 1995, one year after completion, to investigate visible cracking in the tunnel walls. It was found that there were air spaces between the temporary and permanent linings. These were repaired by locally cutting out and replacing the secondary lining (Ferreira AA, 1995). From published newspaper photographs the cracks appeared to be of the order of 500 mm long. It appears that they only affected the secondary lining and were possibly caused by groundwater pressure.

88 A separate unidentified failure was mentioned in 1978 at the Tokyo conference, 'Tunnelling under difficult conditions'. (Muller L. 1978). It appears that a failure of a primary lining regressed along a tunnel and adversely affected a part that had been permanently lined. However, the incident clearly concerned construction rather than long term in-service issues.

89 In February 1996, a failure occurred in the Toyohama hard rock tunnel near Sapporo, Japan when a massive rock fall close to a portal crushed the tunnel. Limited information is available. However, the reported ground movement appears to be on such a scale that the type of lining would not have affected the outcome.

90 Taking account of the historical record and HSE's considered analysis of the in-service issues, there is no evidence to suggest that when tunnels built with NATM primary linings are finally completed and fully commissioned they are inherently less safe for the end user than those constructed by other means. The issue of safety in use is the same for all tunnels. They require regular inspection and proper maintenance and repair. Designers should initially specify the appropriate criteria in these respects. Those responsible for in-service safety should keep these matters under review. Given these pre-requisites, there is no reason why NATM tunnels once fully completed should not be regarded as being as safe for use as any other type of tunnel.

Principal conclusion

Tunnels built with NATM linings, when finally completed and fully commissioned, are as safe as those constructed by other means.

Part 3 - UK health and safety legislation

3.0 Introduction

91 In the UK the legal responsibility for the safety of workers and the public is generally placed on those who create the risk. This part sets out how the UK's legislation, which takes account of EU directives, provides a framework for risk control and risk management.

92 For construction projects there may be many duty holders including clients, designers, contractors and sub-contractors. Each have duties to ensure that their activities do not have an adverse affect on anyone else.

93 Individuals have responsibilities as well. Employees have to take reasonable care for their own health and safety and for others they may put at risk. Directors and similar office holders have to ensure that their corporate bodies do not commit health and safety offences with their personal consent or connivance or through any neglect on their part.

94 It is not the intention of this review to describe comprehensively the legal requirements which may apply to NATM work. These will depend on the way the work is undertaken and the risks involved.

95 There are four principal pieces of legislation to which those involved in NATM work in any capacity should pay attention:

- The Health and Safety at Work etc. Act 1974 (HSWA);
- The Management of Health and Safety at Work Regulations 1992 (MHSW);
- The Construction (Design and Management) Regulations 1994 (CDM);
- The Construction Regulations 1961-1989.

96 Reference should be made to other HSE publications for information about other subordinate legislation.

3.1 The Health and Safety at Work Act 1974

97 The principal health and safety statute is the Health and Safety at Work etc. Act 1974. Some relevant subordinate legislation and Approved Codes of Practice (ACoPs) under the HSWA are listed in Appendix 3. The HSWA places duties on all employers and other with undertakings, be they clients, contractors or designers to ensure, so far as is reasonably practicable, the safety of persons from the hazards arising from their undertakings. Where there is a risk to the public in the event of a tunnelling incident affecting either those on the surface or in structures (whether surface or sub-surface), all duty holders may have to take steps to ensure their safety. All parties to the construction project should be aware that although they may contract others to do work on their behalf they do not thereby relieve themselves of their statutory duties with regard to health and safety.

3.2 The Management of Health and Safety at Work Regulations 1992

98 The MHSW place a duty on every employer to carry out a suitable and sufficient assessment of the risks to which people at work, and others, may be exposed with a view to identifying the measures which need to be taken to comply with legal requirements.

99 The ACoP to the Regulations gives guidance on the principles to be followed when undertaking risk assessments, including the hierarchy of the preventive measures for determining the appropriate response to the assessed risks. Appendix 2 of the CDM ACoP sets this out in the construction context. This is reproduced at appendix 4 of this review. In general terms, the best approach is to avoid the risk altogether by removing or eliminating the hazard. If that is not reasonably practicable reliance has then to be placed more on:

- engineering measures (e.g. containment of the risk within an engineered enclosure, for example, a face-balanced TBM) rather than management systems and systems of work which have the potential for human error to result in failure; and
- measures which protect everyone rather than systems of work which rely on human factors such as judgement and a reliance on people working in closely prescribed ways; and other than by the use of personal protective equipment.

100 It is erroneous to suggest that the route to achieving safety is not important provided that the apparent level of risk is the same. The ACoP to the MHSW emphasises the importance of following the risk control hierarchy step by step. This means that control measures based on, for example, human systems are not acceptable when compared to engineering control systems even when they apparently offer an identical level of safety. The risk hierarchy reflects the difficulties of relying upon human systems alone to ensure safety. Hence it is unlikely that the same level of safety will be achieved in practice by relying on such systems.

101 The MHSW place other duties on employers. These include the duty to:

- make and give effect to health and safety arrangements for the effective planning, organisation, control, monitoring and review of the steps necessary to deal with issues identified through risk assessment;
- make provision for appropriate health surveillance for their employees;
- appoint competent person(s) to assist in securing compliance with health and safety legislation;
- establish procedures for use in the event of serious and imminent danger; and to ensure that only adequately instructed employees have access to danger areas;
- provide health and safety information connected with the MHSW;
- co-operate and co-ordinate with other employers and the self employed;
- take steps as a 'host employers' to provide for the health and safety of others including the self employed who work for them; and
- take account of the capabilities of employees and provide adequate health and safety training including on:
 - recruitment;
 - transfer to new work;
 - a change of responsibilities;
 - the adoption of new work equipment, technology and working methods.

102 Successful management of risk depends on the identification of hazards, the assessment of risk, and the determination of risk control measures, in accordance with the statutory risk hierarchy. Risk assessment techniques should be used to

identify risk and the appropriate control measures which should include due consideration of low probability-high consequence events. The purpose of risk assessment is to guide the judgement of the duty holder as to the measures that should be taken to ensure statutory obligations are fulfilled.

103 Specific health and safety management issues are considered in part 6. Further general guidance can be found in the Approved Code of Practice (ACoP) to the Regulations and in HSE booklet, HS(G)65 (ref. 42).

3.3 The Construction (Design and Management) Regulations 1994

104 The CDM Regulations came into force on 31 March 1995, 5 months after the collapse at Heathrow. The transitional provisions are such that the full requirements of the regulations were not in force until 1 Jan. 1996, and the requirements on designers did not apply until 1st August 1995 in respect of any design where the preparation started before 31st March 1995. It is therefore not yet possible to assess the full impact that these regulations will have on NATM projects in practice.

105 CDM duties will apply to NATM projects. They should be jointly considered with the MHSW requirements. There is a great deal of flexibility in CDM on how the parties to a project go about discharging their duties. This review does not constrain the flexibility that is allowed. Rather, it makes a number of comments about the difficulties that can arise if the underlying principles of the regulations are ignored.

106 CDM places duties on clients, planning supervisors, designers, and principal and other construction contractors. They are comprehensively explained in the ACoP to CDM.

107 Briefly, clients should ensure that:

- they provide relevant information about the site to planning supervisors;
- those they appoint as planning supervisors and principal contractors are competent and are adequately resourced for the particular task (e.g. NATM construction work);
- their principal contractor prepares a satisfactory health and safety plan before starting construction work; and
- there is sufficient time to carry out the design and construction work. This could have major implications if the contractual arrangements are such that the NATM design cannot commence until after the award of the main construction contract.

108 Those who engage designers should similarly satisfy themselves that those they appoint are competent and adequately resourced for the particular task. Planning supervisors are able to advise duty holders on many of their duties. They have to notify HSE about the project.

109 CDM extends the general principles of hazard elimination and risk reduction to construction. They apply equally to the design and construction of temporary works as they do to permanent works. It should be noted that 'design' is a defined term under CDM which includes specification, so those who specify NATM tunnelling methods (including clients and construction contractors) have the legal duties of designers.

110 Designers have a key task in determining the risks which the construction contractors will then have to manage. Planning supervisors have to ensure that all designers (whether of the permanent or temporary works) fulfil their duties by:

- eliminating hazards where possible;

- reducing the remaining risks through design where it is not; and
- providing information about residual risks, which would not be obvious to others in the chain.

111 The design for each element of a NATM tunnel should be fully developed before work on that element commences. NATM should be based on sound engineering principles, and not treated as an *ad hoc* construction procedure selected after design is complete. It is accepted that in any tunnelling work uncertainty will remain about what will be encountered, and that a range of design options will have to be developed to cater for these uncertainties. The essential point is that to meet legal requirements all foreseeable areas of uncertainty should be identified, and the significance of deviations from expected performance determined in advance. Procedures should be put in place to discover when deviations from expected behaviour occur, and that recovery and emergency procedures are in place. Design assumptions should be sufficiently robust that there is time, under all foreseeable circumstances, to identify significant deviations so that recovery measures can be taken long before unacceptable risk arises.

112 Designs for further work can proceed in parallel with earlier construction work provided the health and safety implications are taken into account. Indeed, there may be merit in so doing as this enables lessons learnt from the early stages of construction to be incorporated into later designs. However, given the complex inter-relationships that can arise with tunnelling work, and ancillary processes such as compensation grouting, the time required to develop acceptable designs should not be underestimated.

113 Planning supervisors have duties to ensure co-operation between designers (if more than one is employed on a project). In such cases the planning supervisor needs to take reasonable steps to co-ordinate the health and safety aspects of the designs and ensure that interaction problems are resolved. Clients can help to ensure that practical difficulties are avoided by appointing planning supervisors at an early stage and by putting in place contractual relationships that make co-operation readily achievable.

114 Planning supervisors should ensure that a pre-tender health and safety plan for use in the tendering process is developed. Plans should include:

- general information about the project;
- particular information about significant risks to health and safety;
- information related to assessing the competency and the adequacy of the resources of any contractor;
- information the planning supervisor has, or could reasonably ascertain, which the principal contractor needs to develop the plan for the construction phase.

115 The pre-tender plan should provide sufficient information about the significant risks that have been identified by the designer in relation to the proposed NATM work. This should include a broad indication of the designer's assumptions about the precautions needed for dealing with the risks. Planning supervisors should set out the project specific criteria that have been selected as being appropriate to the competence and necessary resources principal contractor should possess. The range of information principal contractors require to plan and carry out NATM construction safely is considerable. Planning supervisors should assemble this in the first instance. It will relate to the work, the environment and the client teams' proposals (including their management arrangements) for securing safety.

116 Principal contractors then have to develop the plans before commencing construction. The developed plans should include arrangements for:

- managing health and safety risks to all persons; and

- monitoring compliance with legal requirements by all persons.

117 Plans should therefore take account of any focus on the controls that will be necessary to contain the significant risks. Appropriate effort should be expended on NATM related issues given the potential consequences of a major collapse.

118 Planning supervisors are required to gather health and safety information relevant to further construction work following completion of the project. It should be placed in a file and handed to the client.

119 Further guidance can be found in the Approved Code of Practice (ACoP) to CDM.

3.4 The Construction Regulations 1961-1989

120 Detailed requirements specific to the construction industry are contained in 5 codes of Regulations variously made between 1961 and 1989. These are:

- The Construction (General Provisions) Regulations 1961;
- The Construction (Lifting Operations) Regulations 1961;
- The Construction (Working Places) Regulations 1966;
- The Construction (Health and Welfare) Regulations 1966;
- The Construction (Head Protection) Regulations 1989.

121 These apply general standards applicable to all construction work, including temporary structures. It is not the intention to summarise the wide-ranging obligations which arise. Reference should be made to other published works. It should be noted that much of this suite of Regulations is shortly to be replaced.

3.5 Conclusions

122 Any tunnel construction system may be legally acceptable provided that, so far as is reasonably practicable, adequate measures are taken to eliminate or minimise foreseeable risks by good design, and that the necessary management and mitigatory measures are introduced to ensure that residual risks during construction are controlled and kept at acceptable levels.

123 The existing statutory provisions, and in particular the recently introduced Construction (Design and Management) Regulations 1994 (CDM) provide a comprehensive system for the regulatory control of risk, including the assessment of competencies. HSE has concluded that there is no need for further legislation specifically to address the risks from NATM.

Principal conclusion

The existing statutory provisions, and in particular CDM, provide a comprehensive system for the regulatory control of risk including the assessment of competencies. HSE concludes there is no need for further legislation specifically to address the risks arising from NATM.

Part 4 - NATM safety principles

4.0 Introduction

124 Part 4 provides advice on safety principles generally applicable to NATM. The discussion draws largely on the recent HSE experience in assessing the restart proposals for NATM tunnels in London, which was in turn informed by the world-wide accident record. It is not intended as a critique of current UK design and construction practice. As a result some of the comments are particular to London. However, the principles discussed are of much wider application and the references to the conditions in London are given by way of example. Similarly many of the comments apply equally well to other forms of tunnel construction and not just to NATM.

4.1 Overview of risk for NATM projects

Terminology of risk

125 The primary principle laid down by HSWA is that the duty-holder must ensure, so far as is reasonably practicable, health, safety and welfare at work which, in terms of practical risk management, means reducing risks to a level which is 'as low as is reasonably practicable' (ALARP). Whilst a detailed discussion of the concepts of ALARP and risk assessment is outside the scope of this review, and has been dealt with in other HSE publications (refs 45 – 50). A brief explanation of the main terms used in this review may aid understanding of the legal requirements.

- A *hazard* is something with the potential to cause harm.
- A *risk* is a measure both of the likelihood that harm from a particular hazard will occur and its severity or consequence.
- A *risk assessment* starts with the identification of hazards and then goes on to estimate the risk arising from them for the purpose of identifying the measures that need to be taken to avoid or minimise harm.
- The risk to any particular individual, either a worker or a member of the public is the *individual risk*.
- A *societal risk* may arise if there is the risk of a large accident with a consequence on such a scale as to provoke public concern and the likelihood of substantial public injury and property damage.

Risk and consequence

126 Some risks may be so high, or the consequences so severe, that they can never be acceptable even if all practicable steps are taken to reduce the level of risk. In this case, the activity should not be undertaken. Other risks may be so low that no further precautions are necessary. Many risks fall in the tolerability region between these two extremes. Within this region, risk must be reduced ALARP. This means that the duty holder has to weigh the risk against the cost of the measures which will reduce it. The duty holder then has to take those measures which reduce the risk to the lowest level that can be achieved without incurring costs which are grossly disproportionate to the benefit. This means that there is a point beyond which it is not necessary to go, but that the duty holder must err on the side of safety. A risk is tolerable if it is in the tolerability region, and if further risk reduction is impracticable or if the cost is grossly disproportionate to the improvement gained.

128 A tunnel may give rise to individual risk to workers and members of the public. HSE has suggested (ref 49) that the maximum tolerable risk to any member of the

public should be substantially lower than the maximum tolerable risk to workers in any industry.

127 A tunnel may also give rise to a societal risk if a collapse has the potential for injury to the public or significant damage to the built or natural environment. Urban areas have varied land use patterns. Some developments pose a greater societal risk than others. HSE suggests an approach to deal with the issues which arise from different types of land development near to major industrial hazards (refs 47, 48) and this may be of assistance to those considering the location of a tunnel and the methods to be used in its construction. Tunnels should as far as possible be located away from areas of high consequence. Where this is not possible particular attention should be paid to the means of mitigating the consequences of the hazards. There may be locations where the consequences of collapse, no matter how remote the event, would not be acceptable (such as beneath hospitals where rapid public evacuation may not be practicable) and in such cases if construction is to proceed at all methods would have to be used which effectively eliminate the risk of collapse.

129 The implications of this for those involved in NATM are substantial. Whether a risk is tolerable or not is essentially a matter of judgement (ref 49). Such judgements depend on confidence that all significant hazards have been identified and that all reasonably practicable steps have been taken to assess the associated risks and reduce and control them, and also to mitigate the consequences of any serious mishap.

Hazard analysis and risk assessment

130 A risk assessment is required by law. The starting point for a risk assessment is hazard analysis. For example when considering the hazard of tunnel collapse each of the collapse mechanisms described in table 3 should be systematically considered by the risk assessment.

131 Duty holders should undertake risk assessments to establish the control measures which should be taken to ensure safety.

The hierarchy of risk control

132 Part 3 has described legal requirements. Appendix 4 sets out the hierarchy of risk control and sets out the principles which should be followed when deciding whether or not to undertake a project involving risk.

133 Clearly the best option is to avoid the risk altogether. In most cases however this may not be possible. Choices then have to be made about the relative merits of the options available taking the risk control principles into account. In particular, processes which are less rather than more dependent on human systems for their safety should be chosen.

134 NATM is often used alongside other tunnelling techniques especially on large projects. The choice of which technique to use in any particular set of circumstance will be a complex one. Some indicative advice is given in this review but each project must be considered on its merits. The risk control principles require that health and safety is given due prominence and that such decisions are made in the light of a structured approach to risk avoidance, elimination and control.

Hazard identification and risk reduction

135 Hazard identification and risk elimination or reduction specific to NATM require an approach tailored to its particular needs. A comprehensive analysis to determine the possible hazards and the range of potential events and outcomes is required. It is necessary to consider high consequence events (such as face collapses or lining failures involving breakthroughs to the surface) in addition to the more likely events with lesser consequences.

136 Formalised techniques such as hazard and operability studies (HAZOP) and structured hazard analyses (HAZAN) may assist in the process of addressing high consequence events. Hazards need to be identified, risks assessed and control measures and emergency procedures developed. A tabulated analysis may be helpful in conveying the conclusions to others.

137 The knowledge that the safety of the process has been subjected to a risk assessment should not engender complacency. There is a degree of uncertainty associated with any risk assessment and so it should inform, but not dictate, decisions on the management of risk. A major source of uncertainty arises in accounting for human involvement: the liability of an operator to err in the performance of specified tasks and errors of commission or omission by management. The safety of the process depends to a considerable extent on management performing its functions of monitoring to ensure day-to-day compliance with the assumptions of the assessment

4.2 Human factors in risk management

Principal conclusion

NATM is heavily dependent on avoiding human failure.

Introduction

138 Safety of the NATM process is heavily dependent on systems of management and work. People have to make complex judgements to achieve quality in many differing types of work, often under difficult site conditions. In essence safety is dependent on 'human factors'.

139 Human beings are prone to making unintentional errors and intentionally violating work systems. These errors and violations are known as human failures. In this respect, properly designed machines (i.e. engineered solutions) have distinct advantages over people. However, machines cannot carry out safety critical tasks. Reliance is placed on human beings for solving complex problems. Therefore if NATM is to be undertaken safely it is essential that those managing the process understand how human failure happens, what can be done to prevent it, how it can be detected and corrected and how to recover. Indeed failure to consider the issue is human error (refs 43, 44).

140 Human error is not confined to operators. Overly simplistic analysis of incidents, whether minor or of major disaster proportions, can lead to the search for 'scapegoats' at the operator level. However, it must be recognised that human errors occur throughout an organisation. High level errors can play a major part in creating the circumstances where others make errors at the workplace. Thus, in the Zeebrugge incident where a ferry, *The Herald of Free Enterprise*, sailed with its bow doors open, it is overly simplistic to attribute the error to the person who failed to close the door (Sheen, 1987); and, likewise, the presence of flammable grease and detritus in an escalator at Kings Cross where fire caused serious loss of life (Fennel, 1988). Directors and senior managers erred in their approach to these issues.

141 Errors in the choice of tunnelling technology, in design philosophy, in procurement and management systems are examples that can lead to failure which, at first sight, could be attributed to the tunnel worker. If the wrong tunnelling method has been chosen, if the design is flawed, if the contractual and managerial arrangements fail to reduce past and prospective errors, then increased risk of failure during execution should more properly be attributed to these 'high level' errors. This is not to shift the spotlight from operator error. Rather, it is to spread

the beam so that it encompasses every potential for human failure which might adversely affect the outcome of a tunnelling project.

How are errors made?

142 Some references to theory may be useful at this point. Three types of performance or decision making have been described, the *skill-based*, the *rule-based* and the *knowledge-based* (Rasmussen, 1983). These can be integrated into a 'Generic Error Modelling System, GEMS' (Reason 1990). This is shown diagrammatically at figure 15.

Performance levels and error types

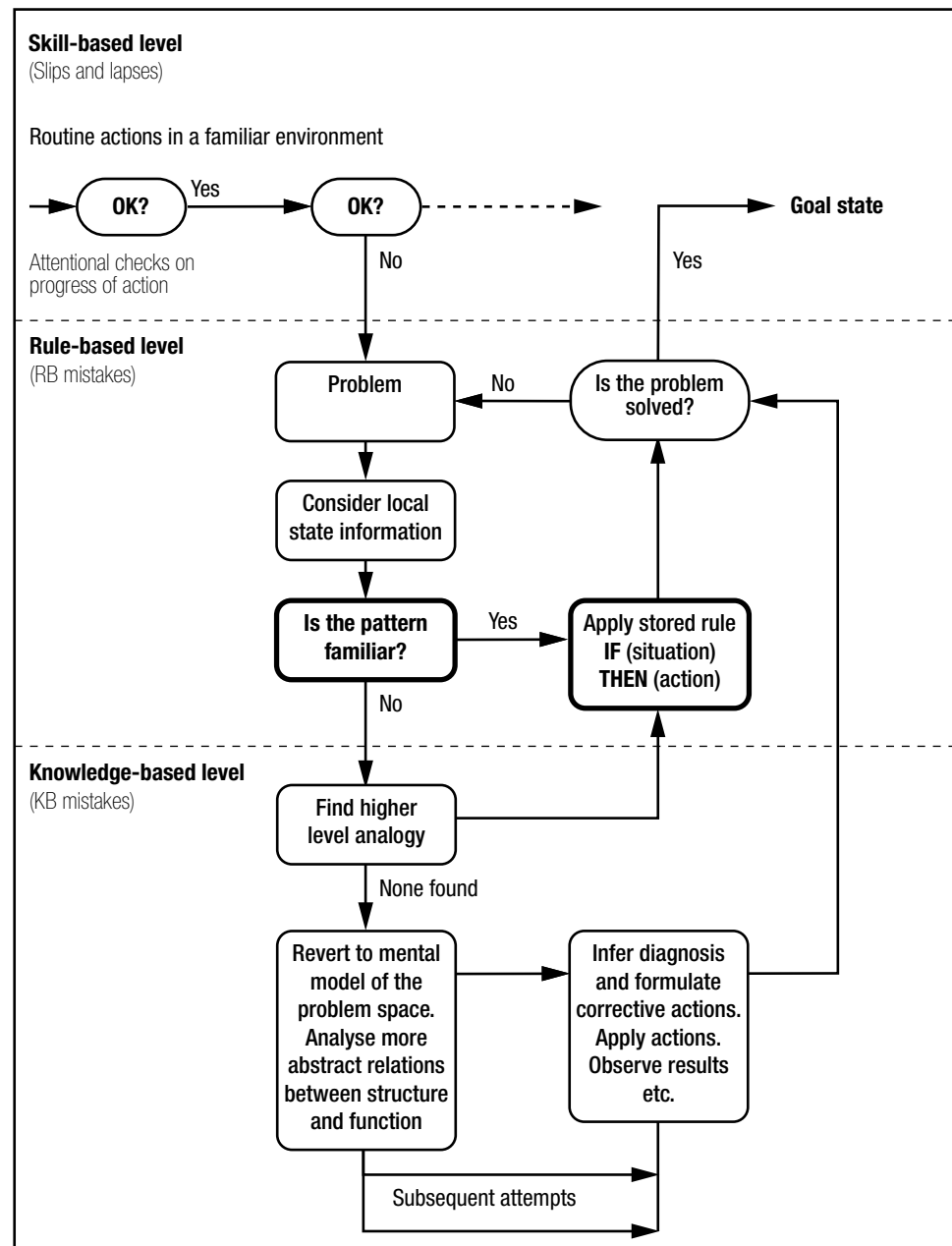


Figure 15 Outlining the dynamics of the generic error-modelling systems (GEMS) (after Reason J, 1990)

143 At the *skill-based level*, actions are governed by well practised routines. Mental arithmetic, key-board skills or other more complex tasks are typical examples. Repetitive operator skills such as shotcrete spraying would fall within this class. These activities are, in a sense, carried out automatically with little conscious

control. Skill-based errors can be seen as slips or lapses. They can come about through inattention, distraction or pre-occupation with some other issue.

144 *Rule-based* approaches are adopted for tackling familiar problems. People apply the 'rule' which most closely matches the current circumstances with successful past experience. The apparent fit and, crucially, the strength of a rule from past successes increases the likelihood of its use. Support from other rules plays a part. Errors tend to occur from a failure to classify the problem. Errors are likely:

- on the first occasion a significant exception is encountered;
- where contra-indications can be reasoned away or do not otherwise attract attention;
- where there is a lot of information clouding the issue; or
- through rigidity of past experience.

Errors can also be made by failing to recall all of the steps needed to solve the problem.

145 Errors may occur when procedures change or a new technology is introduced. Well established rules may be discarded if they appear to be out of date or irrelevant to the new situation. Errors may occur if the reasons for the rules are not fully understood and if new rules are not produced.

146 It is important to differentiate between the 'rules' which people develop for their own use in problem solving and the rules imposed on them in the working environment. Work rules can be, and often are, disobeyed or violated. This can happen for a number of reasons. For instance work rules may:

- be in conflict;
- be seen as inappropriate;
- conflict with a goal-driven desire; and
- be seen to have no strength or relevance due to management inaction when they are breached.

Further information on the point and suggestions for resolving violations can be found in the booklet, *'Improving compliance with safety procedures'* (ref 44).

147 New situations call for a *knowledge-based* problem solving approach. Stored knowledge and analytical processes are needed. Time is required for thought. Errors happen if knowledge is incomplete or incorrect, or if problem solving resources, including functional reasoning and time, are insufficient.

148 Knowledge-based problem solving can be seen to be error-driven since people set local goals, initiate actions, consider the result and then repeat the process. They try to reduce or eliminate the discrepancy between the present position and the one they seek. Knowledge-based mistakes are not easy to predict. Like rule-based errors, knowledge-based errors can be seen as mistakes.

149 Where increasing success at the knowledge-based level is experienced, 'rules' will be developed so that subsequent problems can be resolved at the rule-based level. Likewise, success at the rule-based level can lead to subsequent problem solving at the skill-based level. People prefer lower order problem solving. Hence, the skill-based level will be used in preference to the rule-based approach which in turn will be used in preference to a knowledge-based approach.

How can errors be detected?

150 Errors can be detected by three means:

- self-monitoring. This is more successful at the skill-based level;
- environmental signals. These force a review (e.g. a car driver receives an environmental signal when the car will not move if it is not put into gear);
- from other people who have detected the error.

151 Skill-based errors are easier to detect and correct than others. Immediate feedback helps. This is often unavailable for rule- and knowledge-based problem solving. Detection by independent persons may be the only way to resolve diagnostic errors in complex and stressful situations.

Problems in error detection and correction

152 Increased complexity in an organisation, perhaps compounded by interfaces with others, can lead to problems in identifying and correcting errors. Opaque systems that cannot readily be understood further complicate issues. Poorly assembled organisations and management systems, and inadequacies in training and communication enhance the opportunities for error.

153 The prevention of low frequency-high consequence events provides a further twist. It may not be possible to develop rule-based and knowledge-based problem solving skills in advance. Moreover the presumption that such events should be very infrequent mitigates against identification in rule and knowledge-based approaches.

154 The position is yet more complex where error detection processes do not directly and adversely impinge on the principal activity in hand, whether procurement, design, construction or safety monitoring. The error-driven activity can continue in the absence of an environmental signal. Moreover, detection processes can erroneously be assigned a low order of priority in output-led organisations as they may seem to contribute nothing to goal achievement. Error detection may erroneously be seen, at best, as a neutral influence compared to work more directly linked to output. Indeed, some might consider that error detection mitigates against progress by causing delay and diverting resources. In short, who welcomes bad news, and who increases the resources of its bearer?

Error – avoidance, detection and correction

155 First, it is important to recognise that a skill or rule-based approach can be used by people exercising high level decisions remote from the point of production; and that errors can occur through a lack of understanding. In NATM terms, a client team that has no appreciation of the potential for major collapses during construction will not be mindful of the issue. They may equally err through faulty knowledge-based problem solving. The same can, of course, be true of the shotcreter who may be equally unaware of the crucial significance of his work. It naturally follows that there is a general training need so that, typically, the potential consequences of a major collapse can be part of everyone's mind-set.

156 Second, there is the need to address how the likelihood of human error can be reduced. Human Reliability Analysis (HRA) techniques can be used towards this end. Significant effort has gone into the development of formalised approaches. The reader is directed to other publications (refs 44, 45, 118, 119). It should be noted that specialist knowledge is required.

Developing a control strategy

157 Each duty-holder should analyse the key decisions that need to be taken to achieve the successful completion of a NATM project. Organisations, communications and management systems that reduce the risk of error should be

developed. Existing HSE guidance (ref 43) gives a list of questions which if applied to a NATM project may help both to identify where the control of human factors may play a part in achieving safety, and to the development of a control strategy.

158 A positive safety culture helps. Reasonable shift patterns, adequate staffing, a positive approach to personnel management, good team-working with adequate supervision and clear instructions are exemplars.

159 Most of the key procurement, design and monitoring processes are likely to be knowledge based. They are most amenable to error detection through independent peer review by persons not involved in the decision making process and, ideally, not directly involved in the project.

160 Management should ensure that where rule-based decision making is appropriate, the 'rules' align with safety objectives. The approach of management is crucial in this respect whether in the design office, on the construction site or in the monitoring team. Clear supervisory and documentation systems should focus attention on key safety issues so that internal 'rules' have a strong bias towards safety. Error indicators such as a lack of check signatures on drawings and other paper systems, should be used.

161 All people will work at some time at the skill-based level. Error control should be based on the provision of adequate training time to enable skills to be developed. The working environment must reduce the likelihood of inattention, distract, pre-occupation with some other issue, and stress. Typically for manual tunnelling work, it requires a physical environment that is well lit, provided with safe access, well ventilated and safe from distractions such as moving plant. Visual environmental markers can aid error identification and correction. For example, fully circumferential ribs profile the tunnel for the miner and high visibility depth pins help the shotcreter. Thus, there is a clear error marker if the rib does not fit or the depth pin remains visible. The use of pre-shotcreting inspection sheets is incompatible with a skill-based approach. Rather it calls for a mostly rule-based and sometimes a knowledge-based approach.

4.3 Competence and Training

162 Many of the tasks required safely to design and construct a NATM tunnel require a high degree of competence from the staff and workforce at all levels. It is therefore necessary to adopt a structured approach to selection and employment of competent persons.

163 Competence can be expressed in terms of the possession of the necessary skills, knowledge, and experience for the successful completion of a job function or task. Successful, in this context, encompasses the achievement of the task to an acceptable standard. In certain situations there may be the need for proof of personal achievement in terms of qualifications or other formal assessments of knowledge and skills.

164 Performing a task or function in a competent manner requires an awareness by the individual of the limits of existing experience and knowledge, as well as a willingness and ability to supplement them.

165 At the *skill-based* level it may be a relatively simple matter to confirm that the person has the required competence to achieve a satisfactory level of job performance. The output when the task is undertaken can be easily measured against known and well established engineering criteria. (For example a welder making a weld to a specified profile and quality).

At the *rule-based* level, which is particularly important in engineering, the ability to recognise what rules, whether written or perceived from past experience, can safely be applied centres on:

- where can the relevant rules be found;
- what should be done if the rules do not appear to be appropriate; and
- how will the validation of the rules be validated?

At the *knowledge-based* level defining competent performance may be more difficult but is equally important. Assessment of competence is likely to be influenced by the professional background and depth of practical experience of the individual. Competent individuals have the right level of confidence in relation to the knowledge they possess. They need to be able to appreciate their limitations in making competent judgements, even if there is no benchmark against which such judgements can be readily assessed. In many cases when dealing with new problems, circumstances or processes there may be no 'right' way. The quality of the decision may then depend on:

- the intellectual ability of the individual;
- the rigour with which a satisfactory solution is sought;
- the extent to which an individual can test solutions with his peers; and the
- 'know-how', the ability to translate experience between different conditions of tunnelling.

166 The necessary competencies required by those employed on safety critical tasks should be assessed and suitable training provided to make up any shortfall which is detected. It is not sufficient simply to assume that those who claim to have carried out similar work before have the necessary level of competence for the job in hand. Procedures for training and assessment should be agreed and put in place at an early stage in the project and the approach should extend to all, whether designers, managers, or operatives. Competences should be sufficient to enable everyone involved to understand the key factors which might lead to high consequence events and their role in achieving effective control.

167 Initial assessment of competence may be in a non-working or uncritical environment but there is still a need for assessment under typical working conditions. And the requirement for competence is on-going. Supervision therefore by staff who themselves have the necessary competencies to judge performance is necessary to ensure work continues to be undertaken to the required standards.

4.4 Methodology for addressing the risk of major collapse

Introduction

168 Failure during NATM tunnelling at shallow depths introduces the hazard of major disturbance to the ground. This could cause excessive settlement or the formation of a hole. The hazard presents risk to those at work in the tunnel and others on the surface. It should be considered as capable of causing a major accident. The probability of such an event may be remote but it should nonetheless be recognised and approached in the same way as it is by other industries. This section explains that events which could lead to failure should be discovered in time to enable action to be taken to recover from the emerging situation in such a way that safety is ensured at all times.

'Failure to Danger' and Human Factors

169 NATM safety is particularly dependent on human intervention through management systems and correct working practices, including monitoring, to control work activities and the risk of failure. There are no in-built physical

mechanisms to ensure safety. The system of work may be described as one which 'fails to danger'.

170 Conversely an activity 'fails to safety' if, without human intervention, failure results in a safe situation. A tunnelling example could be the use of a closed face tunnel shield where ground failure cannot normally extend to the surface as it is prevented from moving into the tunnel by the shield. This kind of 'fail safe' activity is inherently safer than one which fails to danger.

171 Though careful planning and design can increase the proportion of activities which 'fail to safety', it will not be possible to eliminate all 'fail to danger' NATM activities. Where the consequence of failure is high, the system should include comprehensive procedures to identify and correct potential failure.

Reducing and managing the Risk of Major Collapse

172 Fig 16 shows a plot of the level of risk against time. Unacceptable risk is indicated by the broken horizontal line (1). The risk from a tunnelling process that is stable is shown by the black horizontal line (2). This residual risk is well below the threshold of unacceptability.

173 The likelihood of failure may depend upon the rate at which risk increases. If the rate of risk development is fast, or there are no readily identifiable precursors of failure, there will be little warning and little prospect of preventing a major collapse. Moreover, the greater the initial level of residual risk, the less the time in which to take action. What must be avoided is a tunnelling method which may create intolerable risk.

174 The chain line (3) shows what happens when increasing risk is not identified until it is too late or no effective action is subsequently taken, perhaps because of a lack of preparedness.

175 The solid line (4) shows what can be achieved where there is early discovery of the adverse event and effective recovery measures are in place through contingency planning. It illustrates a 'discovery-recovery' mechanism which brings about a return to an acceptable level of risk.

176 Early discovery is crucial in providing sufficient time to enable a recovery to be made. It also reduces the levels to which risk may rise. The broken line (5) shows recovery from an adverse event where discovery was late. The shaded area between the broken and solid lines indicates the unnecessary risk due to late discovery. The broken line (5) passes close to and could exceed unacceptable risk levels.

177 A satisfactory discovery mechanism relies on early detection of adverse changes in risk from the information available. This requires planned pro-active monitoring in which timely, reliable and easily interpretable data are collected, critically examined by competent persons and the conclusions passed to an appropriate level of management for any necessary action. Passive monitoring systems are wholly unsatisfactory.

178 The more frequent and risk directed the pro-active monitoring, the greater is the opportunity for early discovery. The probable rate of development of adverse changes and the time needed to effect recovery are factors which should be taken into account when considering the monitoring frequency.

179 The recovery mechanism has two principal elements. These are 'decision making' and 'action'. Management structures that minimise the time taken to reach decisions and contingency plans that facilitate recovery actions are crucial to

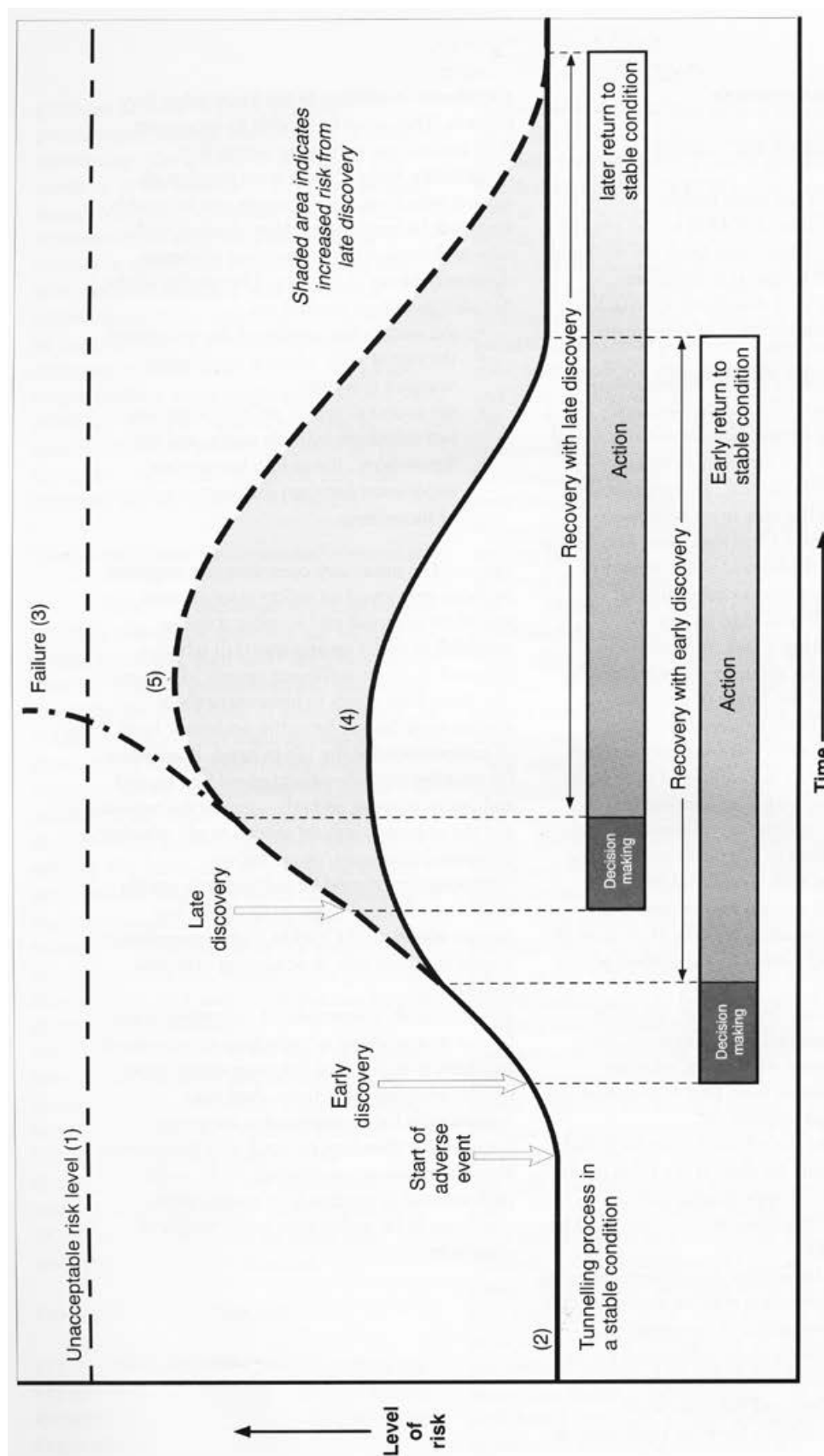


Figure 16 Graph showing 'Discovery-Recovery' model

controlling the level of risk. The longer the recovery process, the greater the risk that will arise and the more likely a major accident. Importantly, the recovery process should not cause the risk to rise to an unacceptable degree.

180 However, complete reliance cannot be placed on the discovery-recovery mechanism to secure safety. The prospect of a major failure has to be addressed before the commencement of the activity.

4.5 Safety through buildability

181 The importance of buildability derives from a recognition that design is intimately involved with construction. Designs which take account of the ease of construction or 'buildability' will greatly facilitate the achievement of quality during construction. And this will lead to a better product and improved safety.

182 A final review of designs and specifications for buildability should be made before they are released for construction. The objective should be to reduce the level of variability and uncertainty arising during construction process.

183 Designers will presume a certain rate of advance and elapse of time between excavation and ring closure for the purposes of predicting likely stresses in the lining and probable surface settlement. Buildability reviews should determine whether the designers' criteria can be met. If not, the consequences for the design should be reviewed or increased resources should be provided. There may be knock-on implications for support operations (e.g. transportation etc) that may have safety implications.

184 Buildability reviews should consider the sequence of construction where multi-tunnel systems are proposed. Caution should be to the fore. There may be limitations in terms of the separation that must be maintained between working faces to consider. The possible advantages of completing a single tunnel before driving subsequent ones should be noted. This may extend to the formation of the inner (or permanent) lining.

185 Closely juxtaposed tunnels (say, in the region of one to two tunnel diameters) should be subject to particular review. A range of construction proposals should be considered where the separation is small. For instance, it may be that advanced construction of a stiffened common wall is preferable.

186 Significant tunnel intersections should be subject to careful safety consideration as should proposals for initial break-outs from shafts. For example to avoid problems from slender pillars of ground careful consideration should be given to forming oblique junctions by the construction of an enlargement in the major tunnel.

187 The sequencing of other work, such as compensation grouting, other nearby construction activities and the presence of existing underground structures and foundations which may have a significant bearing on the NATM construction works should be carefully considered and uncertainties resolved.

188 Ease and simplicity during construction will lead to a greater likelihood of success and reduce human error. Design solutions that give rise to immediate indicators when crucial work is out of tolerance should be a high priority. 'Buildability' will speed construction, and reduce the likelihood of settlement and the connected need for additional processes such as compensation grouting.

189 Contractors need to appreciate the sensitivity concerning particular parts of the design in achieving structural integrity and this should be made clear by designers.

Likewise, designers should appreciate the opportunities and limitations in securing health and safety from the construction processes available. Two crucial issues concern stability of the face and the continuing integrity of the sprayed concrete lining.

190 Safety through buildability can be found as an important theme throughout part 5 – designing for safety.

4.6 Quality

191 The achievement of quality is essential if a NATM project is to be completed successfully. Quality assurance (QA) is a means of demonstrating that appropriate quality standards have been met through quality control.

192 For NATM projects QA can play an important part in an overall system of risk management and control. QA systems should be properly tailored to meet the project needs. The general principles of achieving quality are best considered at an early stage of a project. They should then be applied when safety critical issues are considered. Senior staff should pay close attention to quality where the consequences of error involves the potential for high risk. Their commitment to quality and the standards set should be understood by everyone involved with the project.

193 The principles of quality can be applied to all aspects of a NATM project. Given the importance of people and design to the safety of a NATM project the application of QA to the processes of staff selection, design and construction planning is just as important as applying it to construction. For example QA procedures could be applied to:

- determine key performance indicators, and reports to designated senior managers;
- the resolution of demarcation issues between design and construction contractors;
- material supply by external suppliers where interruption in supply could have safety implications (e.g. shotcrete delivery);
- establish inspection, testing, monitoring and review protocols.

194 If a tunnel lining is to perform adequately, both during and post construction, it is essential that it is built to an acceptable quality standard in accordance with the designer's intentions. Quality standards should be considered at every stage of the construction process not just in relation to the integrity and quality of the completed structure. It is generally more difficult to control quality of site activities than for workshop based activities. Quality assurance is particularly important for NATM work which relies heavily on in-situ processes. The following activities may require particular attention to achieve the specified quality standard:

- excavation of an accurate profile;
- maintenance of correct face profile and support measures;
- accurate placing of reinforcement;
- sprayed concrete thickness;
- sprayed concrete strength;
- construction of joints in lining.

195 Failure to achieve an adequate standard in any of the above either singly or in combination may compromise the integrity of the tunnel. To monitor these critical processes and ensure that materials and workmanship remain within defined standards QA arrangements should be put in place before work commences.

196 Acceptable standards should be defined on a rational basis, which specify permissible limits of deviation based on the use of sensitivity analysis. Construction methods and sequencing should be developed at the design stage to ensure buildability of the design detail to meet these standards.

197 The design process should identify quality parameters that are important to the integrity of the structure, and locations such as construction joints where the achievement of construction quality is particularly critical. Face stability and lining integrity are issues central to the safe conclusion of NATM tunnelling. Particular attention should be given to them when devising control systems. Senior project managers should ensure that they are able to exercise sufficient control over these issues. The regime to monitor compliance with quality standards, or quality assurance, should be integrated with the design process.

198 Trials may need to be carried out to confirm that the design detail can be consistently constructed to meet the required standards. Construction should not commence until the design and construction process have been reviewed in the light of the analysis of all data obtained from the trials.

199 Control of more repetitive issues and tasks such as materials, components, face excavation, and lining construction are best subject to quality control systems tailored to production activities, and incorporating the required levels of supervision. Quality control measures should:

- target all safety critical issues;
- have the active commitment of senior managers and have their involvement through key performance indicators;
- have the confidence and commitment of those subject to the controls;
- have sufficient independence from those whose work is subject to control;
- include the setting of 'fit for purpose' performance standards;
- be carried forward by formalised procedures;
- be capable of reducing uncertainty to acceptable limits;
- be capable of identifying unsatisfactory performance;
- be sufficiently timely to:
 - identify adverse trends at the earliest opportunity;
 - enable remedial measures to be taken; and
 - where necessary, enable emergency procedures to be successfully implemented;
- involve pro-active routine scrutiny; rather than a fault driven passive scheme;
- be structured to avoid corruption through human failings;
- adopt a 'no blame' philosophy so that failings are not covered up; and
- involve formalised systems e.g. quality assurance.

200 Quality checks, both during the construction process and subsequently, should be carried out by suitably qualified, competent independent personnel. Data obtained should be regularly reviewed along with other key monitoring information in order that developing trends, particularly falling standards, can be addressed promptly. There should also be effective procedures for ensuring prompt reporting and rectification of non-compliances.

201 The advisability of independent peer review of quality also extends to the construction stages of the project. It has been traditional in the UK, for the principal designer to review the design and planning of the methods of construction to ensure that these meet the requirements of the permanent design and do not introduce unnecessary health and safety risks. In addition, due to the high consequences of poor quality construction work, there is a need for independent quality control of the construction work. Again in the UK, this has traditionally been carried out at the operative level by a system of peer review through detailed on site

inspection. An independent review procedure is more appropriate for high consequence activities such as construction of the tunnel heading and lining. Self-certification schemes are unlikely to offer the same level of assurance.

Principal conclusion

The achievement of quality is essential if a NATM project is to be completed successfully.

Part 5 - Designing for safety

5.0 Introduction

202 Advice on the application of these principles in the context of NATM tunnel construction, with particular reference to London clay is given in part 5. And it provides advice on how the risk may be either eliminated, or reduced and residual risks controlled to acceptable levels (figure 17).

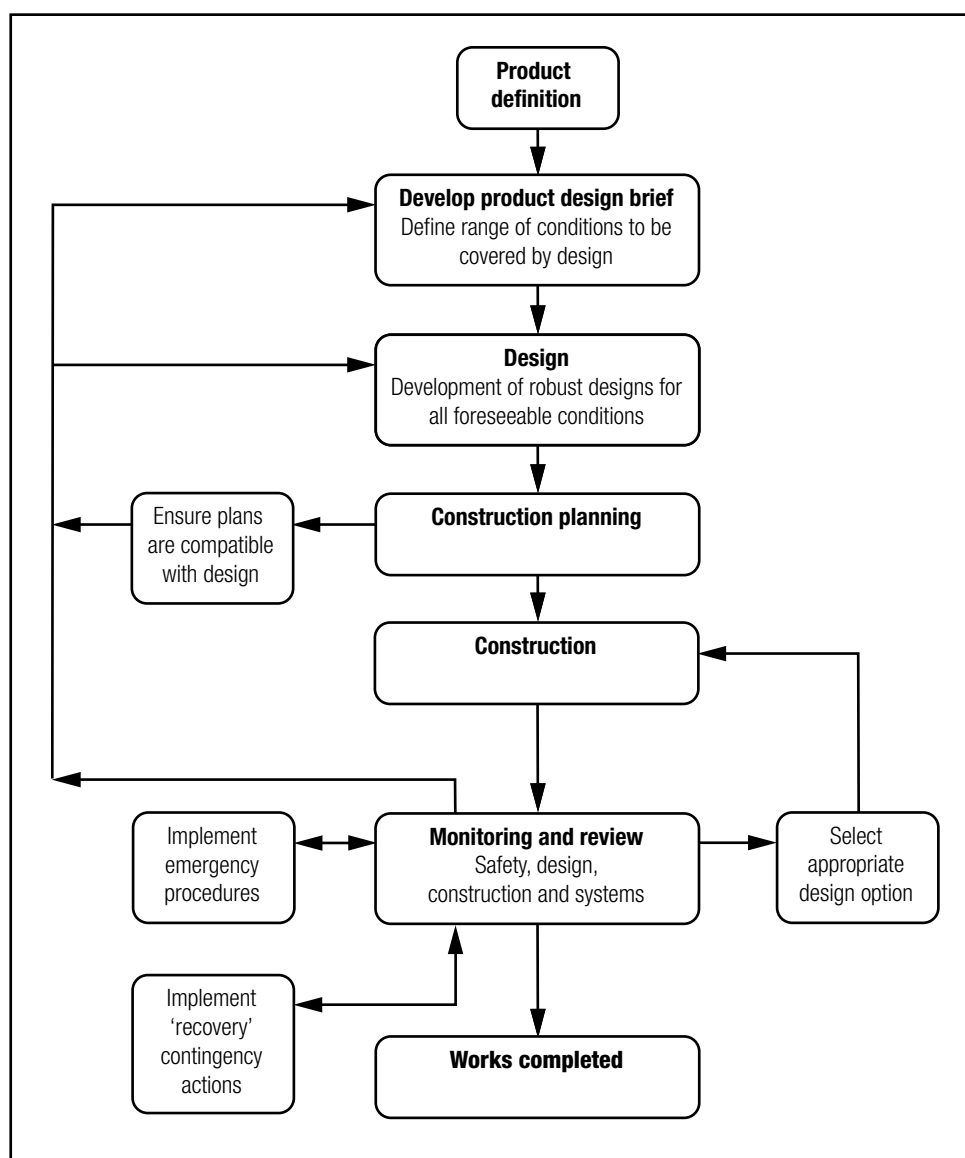


Figure 17 The design and construction process

5.1 Ground Investigations

Health and safety requirement for ground investigation

203 The review of NATM failures shows many tunnel failures have been attributed to unexpected ground conditions. It is not known if these were due to avoidable ignorance or to some previously unknown characteristic of the ground. In developed urban areas, the latter is rare.

204 In most geological environments, possible ground conditions include some which will cause failure of a NATM tunnel if encountered unexpectedly. The safety consequences may be significant for people in the tunnel and on the surface. The main safety objective of ground investigation for NATM is to minimise the likelihood of encountering unexpected conditions.

205 The cost of ground investigation is significant both in terms of time and resources. However, safety may be compromised if this is skimmed, and even greater costs may be subsequently incurred. Without proper investigation the ground remains a hazard.

206 The general principles of ground investigations are well documented. (B.S.I. 1981, I.C.E. 1991). Three phases of investigation are normally required; the 'desk study', the main ground investigation, and investigation during construction. The objectives are to:

- identify and describe the range of ground conditions that could be encountered;
- predict where, if at all, those conditions will be met;
- review continuously predictions against conditions found during construction.

207 The first phase should be based on studies of the geology to obtain an understanding of the geological processes which have affected the ground. Previous construction and mining experience in similar geological environment(s) should also be considered. Studies should identify all possible ground conditions so that the likelihood of encountering unexpected ground conditions is negligible.

208 This first phase may not require any new works such as boreholes. For this reason it is often referred to as a 'desk study'. The stages of a desk study are:

- collection of all available geological and ground investigation data along the route and from the surrounding area that may provide further information on the conditions likely to be encountered, including experience from previous works;
- interpretation of these data and preliminary identification of the geological hazards applicable to the methods of tunnel construction;
- planning and specifying the ground investigations.

Principal conclusion

Ground investigations throughout must ensure that there is no likelihood of meeting unexpected conditions of a critical nature.

209 Geological hazards are any natural variation which result in engineering properties being significantly and adversely different from those assumed in design. In London clay this will include properties of ground mass which differ from those of laboratory samples or small scale field tests (e.g. variations due to discontinuities and material anisotropy), variations in material type, unconformable features and disturbances due to fault movements in underlying bedrock.

210 An analysis of geological hazards should be carried out to determine the extent of the ground investigations required. This should form the geological part of risk assessment.

211 The objective of the second phase of ground investigations is to determine conditions at each point along the tunnel route. Ground conditions may change significantly over short distances. Closely spaced investigation may be necessary to

make reliable predictions of the ground conditions. On unobstructed sites, hazards can probably be located by conventional ground investigation techniques such as boreholes and geophysical survey. To obtain a thorough understanding of the geology there should be:

- ground investigation works which supplement and confirm prior information and data. (This may require several stages of investigation and interpretation depending upon the health and safety risks associated with the geological uncertainties);
- geological and geotechnical interpretation of ground information and data;
- preparation of interpretative reports and ground models for design;
- confirmation of geological hazards and variations in ground properties that may be encountered.

The limitations of the ground investigation techniques used must be understood.

212 In addition to identifying all geological hazards, the first two phases should provide sufficient information for the purposes of lining and heading design, and where applicable settlement estimates, to be undertaken. Ground investigation should be substantially complete before construction, deferring only that which is impracticable to the third phase.

213 If there is a significant likelihood of encountering geological hazards whose location is unknown, and determination of their location in advance is impracticable, then the tunnel design should specify methods for finding them as construction proceeds. This may be the case, for example, if the land above the tunnel is heavily developed. Tunnelling methods should be chosen which can cope with any geological hazards which have not been located.

214 For example, it may not be practicable to locate all unconformable features in London clay. These may be located by drilling near horizontal exploratory holes from within the tunnel.

215 The third phase is carried out during construction. Ground investigation data should be kept under constant review and reinterpreted as more detailed information becomes available. The objective is to maintain up to date predictions of the ground likely to be encountered. This phase should be fully integrated into construction risk control and management systems. Investigation works typically carried out are:

- detailed geological logging of the ground exposed during construction;
- probing ahead of and around the tunnel face;
- interpretation of fresh data and correlation with previous information;
- prediction of ground conditions likely to be encountered.

Ground information from all construction works should be collated and interpreted, (e.g. pilot tunnels, drilling for grouting arrays or instrumentation).

216 By these means ground conditions should be known with a high degree of certainty and risk should be controlled to tolerable levels. Unforeseen conditions are only likely to result from a failure to carry out necessary investigation. There are no technical reasons why unforeseen ground conditions causing intolerable risks should be encountered in London clay.

Geological hazards in London clay

217 In order to illustrate the hazards that should be identified by ground investigations the main geological hazards in London clay are briefly described below. This list is not exhaustive. Part 2 provides further examples.

Falls of clay blocks from the tunnel face

218 As a result of its complex stress history, London clay contains many near horizontal discontinuities or breaks. (Note: the term 'discontinuities' is used to describe all breaks in the clay mass whatever their origin). In addition it contains inclined and near vertical discontinuities. The information available suggests that the orientation of these discontinuities varies across the London Basin and with depth (Fookes and Parrish, 1969). Generally, they appear to be ordered into two or three near vertical discontinuity sets (i.e. groups of discontinuities with a similar orientation and genesis) and a few widely spaced inclined discontinuities.

219 In places movement within London clay has allowed discontinuity surfaces to absorb water and become swollen. This swollen clay is relatively weak. When encountered at an unfavourable orientation in a tunnel excavation face, a substantial block may slide along the discontinuity and fall from the face (Harding, 1981). Movement is likely to occur rapidly and without warning and anyone standing nearby may be struck. Fatalities have occurred. These blocks are known as 'greasy backs' on account of the texture of the discontinuity surface.

Variations in permeability

220 London clay is a sedimentary deposit of fine soil ranging from fine sands and silts to clays. It was deposited in a sequence of sedimentary cycles resulting in strata each typically 1 to 2 metres thick. Each stratum may vary from a fine sand to a clay with finer material at the top of the cycle, (King, 1981). There are substantial differences in permeability. As a result the mass permeability near tunnel faces depends upon the strata encountered, and is anisotropic.

221 London clay has been subject to geological processes which have caused the formation of clay stones. These are typically some 300 mm in thickness, a metre or so in plan dimension, and usually found in near-horizontal bands. When they are encountered water frequently seeps out of the adjacent clay.

222 Variations in material, and the effects of discontinuities lead to local variations in the mass permeability. This may affect the rate at which the clay can swell from the stress changes induced by tunnelling. This directly affects the time tunnel excavation faces are stable which may vary significantly.

Scour hollows and piping

223 Large areas of disturbed ground extending through the London clay probably present the greatest hazard to tunnel construction. These are typically some 50 metres in diameter and filled with water bearing loose to medium dense sands and silts (Baker and James 1990). Should an unsupported tunnel face unexpectedly encounter such a feature face collapse, accompanied by a rapid inflow of water and unconsolidated sediments, is almost inevitable.

224 These features are found throughout the London Basin. Most recorded cases are in central London, alongside the River Thames between Battersea and the Isle of Dogs, (Simpson et al 1989). Other instances are near Heathrow Airport adjacent to the intersection of the M4 and M25 motorways (Baker and James, 1990) and at Highbury in north London (NCE, 1984).

225 Smaller areas of disturbed ground, typically some 10 metres in diameter, may be encountered around the edge of the London Basin where the clay is relatively thin. They are thought to be due to 'piping' of water under artesian pressures through fissures in the clay. After formation, the 'pipes' were then infilled by unconsolidated water bearing sediments.

226 In south London the surface of the London clay contains deeply eroded valleys formed by tributaries of the Thames (Jones, 1981). As a result of the base level of

the Thames rising, these valleys have been filled by unconsolidated sediments. These sediments present a significant hazard to tunnelling. It has been reported (Hutchinson, 1991) that they may locally extend to some 30 metres below the general level of the top of the clay.

5.2 Engineering technology

227 Those involved in a NATM project should seek to take advantage of technological and technical progress, which can offer opportunities for improving working methods and making them safer. This is a requirement of the MHSW – see part 3 and appendix 4. Improvements in technology are continually being made and, even where those involved have extensive experience of such work, a technology review should be undertaken. The purpose of the review is to assist the selection of the most appropriate technologies so that the designer can then use them to best effect. This becomes especially important if new technologies are being used, or if existing technologies are being used in unfamiliar ways, or in circumstances which differ from those previously encountered.

228 The views of suppliers of constituent elements of the technology (such as computer programmes for design, instrumentation and data evaluation equipment, or plant and materials for construction) should also be sought to obtain tried and tested equipment. The technology review should establish that the technologies used are mutually compatible. Compensation grouting, for example has been deployed without a sufficient assessment being made of its influence on the tunnel. Universities and research organisations can play a valuable role in the investigation and study of untried methods of working.

Previous experience

229 The technological review process is likely to draw heavily on previous experience. This may come directly from those in a team, from others or from written records whether unique to a team member or available in the wider public domain.

230 Previous experience of particular relevance to ensuring safety would include knowledge and understanding of:

- available tunnel design and construction technologies and their limitations;
- previously successful approaches to design, construction and monitoring;
- site specific information such as the geology and existing land-uses;
- people and organisations with the experience, expertise, skills, resources and competencies to undertake the work.

231 Considerable benefits can be gained by pooling the experience of all parts of the team. For example, the design should take account of the practical limitations of the available technologies. Recent practical experience of NATM construction should be reviewed and incorporated.

232 The significance of previous NATM experiences should be carefully assessed. It is the understanding of how such factors as size, rate of advance, ground properties, and depth can be applied to the different circumstances of the new project that is crucial. Group reinforcement of erroneous views, based on a misinterpretation of common previous experience, can lead to mistakes. Incomplete investigations into relevant issues may result.

233 There is great benefit from the wide dissemination of experience if progress is to be made where current knowledge is limited. Publication also brings benefits from peer review and public debate. There is a dearth of published information

relating predictions to out-turns from NATM tunnels. This adversely affects confidence in the ability of practitioners successfully to apply the technique.

5.3 A risk-based approach to NATM design

234 Design is defined in CDM as ‘in relation to any structure includes drawing, design details, specification and bill of quantities (including specification of articles or substances) in relation to the structure’. This section of the review considers design in these terms. A risk-based approach to design and management is required to reduce uncertainty to acceptable limits. Wider aspects of design are considered in part 6.

235 Typically two design procedures have been adopted for the design of a NATM tunnel:

- design by calculation, including semi-empirical methods; and
- prescriptive design.

These two procedures have been supplemented by the observational method applied during the construction phase. On major NATM tunnel projects these procedures are likely to be used together to manage the uncertainties in the various parts of the NATM process.

Design by calculation

236 Engineering structures are normally associated with design by calculation, using conceptual models that are based on a method of analysis which is believed, within reasonable bounds of accuracy, to represent the real behaviour. It is customary to apply ‘factors of safety’ to the value of the variables input to the analysis. These factors are intended, in part, to allow for the uncertainties in the design process. These uncertainties arise for several reasons. For a proper consideration of the health and safety risks arising out of design, each reason should be considered separately (or partially). This approach has resulted in the widespread adoption of ‘partial’ factors of safety, which allow for the uncertainty caused by specific elements of the calculation.

237 Partial factors of safety are used to:

- provide for the uncertain strength of the materials;
- provide for the uncertainty in determining the loads applied;
- provide for the approximate nature of the method of analysis (semi-empirical methods); and
- to control the collapse behaviour of the structure.

The health and safety aspects of these allowances are discussed in the following paragraphs.

Uncertain strength of the materials

238 The allowance for the uncertain material strength is typically based on a statistical analysis of the measured variation of a strength value. The objective is to use a value in the design calculations which has a low, or negligible, probability of being unsuitable. The procedure for selecting the value is usually specified in an engineering code of practice.

239 In NATM tunnels, the construction materials are rarely unique and, in the absence of specific engineering standards for tunnel construction, it may be appropriate to use criteria established for other forms of construction with possibly some additional allowance for the more difficult working environment in a tunnel.

For a sprayed concrete lining, the partial factors of safety on material strengths recommended in UK engineering standards such as B.S. 8110 *Structural Use of Concrete* have sometimes been applied.

The uncertainty in determining the loads applied

240 For many engineering structures, the uncertainty in the external loads applied to the structure is treated in a statistical manner, which, in principle, is similar to that adopted for material strengths. This approach is usually applied to external loads which vary randomly during the life of the structure, for example, floor loads in buildings and traffic loads on bridges. The effects on the structure of the variation in the load are often allowed for by applying a load factor to the estimated load.

241 This approach is now always appropriate for external loads which can be defined, and either do not vary, or vary in a relatively predictable manner, during the life of the structure. For this type of load, the variation due to random effects is negligible, and hence a statistical approach is not necessary. Direct consideration of the factors causing the external load is preferable.

242 The load on a tunnel and its ground support system (including the adjacent ground) is predominantly due to the effects of:

- the weight of the ground;
- building or structural loads applied to the ground; and
- the ambient water pressures.

With the exception of any traffic or live building loads, which normally only account for a small fraction of the total load, these factors do not vary in a random manner.

243 The ground load that is applied to a tunnel lining is the result of complex ground/tunnel interaction, and is affected by the engineering behaviour of both. It is not an independent, or nearly independent, external load similar to those to which UK structural code load factors are normally applied. Hence factoring the external loads (i.e. weight of the ground, etc) applied to a tunnel ground system may not improve the safety of the design.

Approximate nature of the method of analysis (semi-empirical methods)

244 At present, it is impractical to prepare calculations for the construction of a tunnel which takes sufficient account of the complexity of the properties of the ground, the ground support system and the geometry of intermediate phases of construction. Therefore, despite their apparent rigour the design, calculations will be approximate and may not accurately represent conditions in the ground and tunnel. The uncertainty is due to the limits of current technology and can only be overcome by further research, including comparison of tunnel behaviour predicted by calculation, with that actually observed in a wide range of conditions.

245 Though the data and available technology may be limited, the uncertainty in the design calculations can be reduced by calibrating the design predictions against the behaviour of comparable completed tunnels, especially project specific trial tunnels.

246 In this review, a design based on a careful comparison of predictions made by calculation with observations made on actual structures, is referred to as semi-empirical. When semi-empirical methods are used for design, the calculated predictions are factored by a value appropriate to the design case being considered. These values (partial safety or load factors) may be applied singly or in combination with other factors, for example, a partial safety factor on sprayed concrete strength. International tunnel engineering practice has shown that the factors appropriate to semi-empirical tunnel design may differ significantly in value

from the factors given in UK design codes for application to other engineering structures.

Control of the collapse behaviour of the structure

247 If the input values to a design calculation for a concrete structure are factored, the proportions of the structure deduced from the calculation can be controlled in such a way that certain components of the structure will fail first. As a result a particular mode of structural failure can be eliminated.

248 A well known example of this procedure can be found in the partial factors of safety adopted in reinforced concrete design. These factors ensure that in the event of the structure being overloaded large deformations occur at loads well below that which will cause the structure to collapse. These deformations warn the users that the structure is in distress and enable contingency actions and emergency procedures to be implemented safely. Hence, the health and safety risk to the users is minimised.

249 This technique is particularly relevant to the design of the sprayed concrete linings in a NATM tunnel. A failure which develops rapidly may not be detected by the tunnel monitoring systems in time for the contingency measures to be implemented. Hence, for safety reasons, the sprayed concrete lining to a tunnel in soft ground should be designed to give ample visible warning of an impending brittle failure.

Prescriptive Design

250 In this review prescriptive design refers to design based on a distillation of prior construction experience which is not project specific. In situations where conceptual models are not available prescriptive design may be necessary. A similar prescriptive approach may also be adopted for well tried design details which are difficult to design by calculation. In NATM tunnel design, prescriptive design is only applicable when there is substantial relevant previous experience.

251 The risks associated with prescriptive design are difficult to assess as the variables controlling the performance of the design are generally not known. If the design feature has been widely used successfully in similar situations then it may be reasonable to assume that the feature will perform satisfactorily again. However, for most NATM projects there is insufficient local experience to provide the necessary confidence in a totally prescriptive design approach. For risk assessment purposes, it will probably be necessary to carry out design calculations.

Development of a robust design

252 In engineering design the dimensions, strength and articulation of the structure should be chosen so that the structure can withstand the likely loading. A robust design, which is essential, is one where the risk of failure, or of damage, to the structure is extremely remote during its design life.

253 The predominant causes of uncertainty in the design of a typical tunnel project can be classified into three groups; those related to:

- the ground conditions prior to construction,
 - the type of ground, both material and discontinuities,
 - the ground water regime,
 - the distribution of stress within the ground,
- the response of the ground and tunnel to the construction works,
 - the mechanical behaviour of the ground,
 - the interaction between the tunnel lining or ground support system and the ground,
- variability of construction.

254 Though theoretically distinct, in practice these groups overlap as, for example, it may be impossible to determine if a poor prediction of ground behaviour is due to errors in predicting the type of ground or its mechanical behaviour. Fortunately, this difficulty becomes less important when the means of reducing the risks are considered.

255 Uncertainty related to ground conditions prior to construction can be reduced by adequate ground and site investigation. This should include carrying out exploratory works such as boreholes, and studying the natural geological processes that have formed the ground, and prior construction works and mining.

256 Major variations, both actual and possible, in the ground conditions along the route of a tunnel may be allowed for in design by grouping the ground conditions into classes. Within each class the ground and tunnel interaction is expected to be sensibly constant and a separate design is produced for each. The criteria for identifying the ground classes have to be specified as part of the detailed design. During construction the ground class is determined by methodical observation of the excavation and the tunnel behaviour and by probing ahead, so that the appropriate tunnel design is selected.

257 There are practical limits to the detail in which an investigation can describe the ground to be encountered by a tunnel. Therefore, the prediction of the response of the ground and tunnel lining or ground support system to the construction works, will be conditioned by the detail available from the investigations, from which a 'worst case' is derived. For example, if the detail is imprecise and the relevant ground and material properties and initial stresses can not be determined accurately enough, it may be necessary to carry out several analyses of the tunnel lining to assess its likely behaviour over the range of uncertainty.

258 Causes of uncertainty in a typical tunnel project interact in a complex manner and generally, a single reliable prediction of the engineering behaviour of, for example, the tunnel lining, cannot be made. When necessary, for example in areas of high risk, this difficulty can be overcome by making several predictions to determine the sensitivity of the design to the range of possible ground conditions.

Principal conclusion

A robust design is essential. Design for each element should be fully developed before construction of that element commences. Design modifications should only be used to enhance a robust design.

The observational method

259 Normally, during construction, the behaviour of NATM tunnels is monitored. The monitoring procedure adopted is often described by the proponents of NATM as an application of the 'Observational Method', (Peck, 1969a). This 'method' is widely used in civil engineering, in particular for the design and construction of major excavations, embankment dams and underground works, and for processes ancillary to NATM construction, such as compensation grouting.

260 Since 1969 the observational method has been developed. The European Pre-standard ENV 1997-1:1994 *Eurocode 7: Geotechnical Design – Part 1: General Rules*, includes the following definition.

"1) P Because prediction of geotechnical behaviour is often difficult, it is sometimes appropriate to adopt the approach known as 'the observational method', in which

the design is reviewed during construction. When this approach is used, the following four requirements shall all be met before construction is started:

- *the limits of behaviour which are acceptable shall be established.*
- *the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.*
- *a plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage; and with sufficiently short intervals to allow contingency actions to be undertaken successfully. The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.*
- *a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits.*

2) P During construction the monitoring shall be carried out as planned and additional or replacement monitoring shall be undertaken if this becomes necessary. The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if this becomes necessary."

261 The Eurocode is one of a series intended to serve as reference documents for proving compliance with the Commission of the European Communities' Construction Products Directive and as a framework for drawing up harmonised technical specifications for construction products (i.e. the structure) rather than the health and safety of those constructing it or those affected thereby. Nonetheless, the definition provides a helpful starting point for the purposes of this review provided the wider issues of health and safety are borne in mind.

262 Eurocode 7 is clear that the observational method is a process in which a pre-determined '*design is **reviewed** during construction*'. The code lists the requirements which should be met before construction commences. It includes the requirement that the design is such that there is '*an acceptable probability that the actual behaviour (of the tunnel) will be within the acceptable limits*'. From a safety viewpoint this leads to the conclusion that the design developed before construction work is started should be robust.

263 The justification given in Eurocode 7 for adopting the observational method is that the '*prediction of geotechnical behaviour is difficult*'. Under UK legislation, if the health and safety risks are adversely affected, the fact that the prediction of geotechnical behaviour is difficult does not justify a less than fully robust design approach.

264 Eurocode 7 also makes it clear that a plan of contingency actions should be prepared before construction work starts. Such plans must clearly relate to the possibility that behaviour could be outside acceptable limits. No advice is given on how acceptable limits are set: they should be set with due regard for safety so that in conjunction with the monitoring, the contingency actions can be implemented without intolerable risk occurring. The design should remain robust throughout.

265 The objective of monitoring under the observational method is '*to allow contingency actions (planned before construction is started) to be undertaken successfully*'. Design review is a process of critical examination of product performance: review is not a process for design modification, as work proceeds.

Principal conclusion

The 'observational method' is a process in which a pre-determined design is reviewed during construction. It is not a method of design or design modification.

5.4 Monitoring

266 Monitoring during construction should be undertaken to ensure safety (figure 18). Additional monitoring may be required where there are safety implications for others e.g. gas mains, underground railways, etc. There are two principal objectives:

- design monitoring; and
- construction monitoring.

Failure to meet standards is an indicator of ineffective management; and that the project is at risk. Monitoring systems should collect qualitative and quantitative data sufficient to meet all these needs.

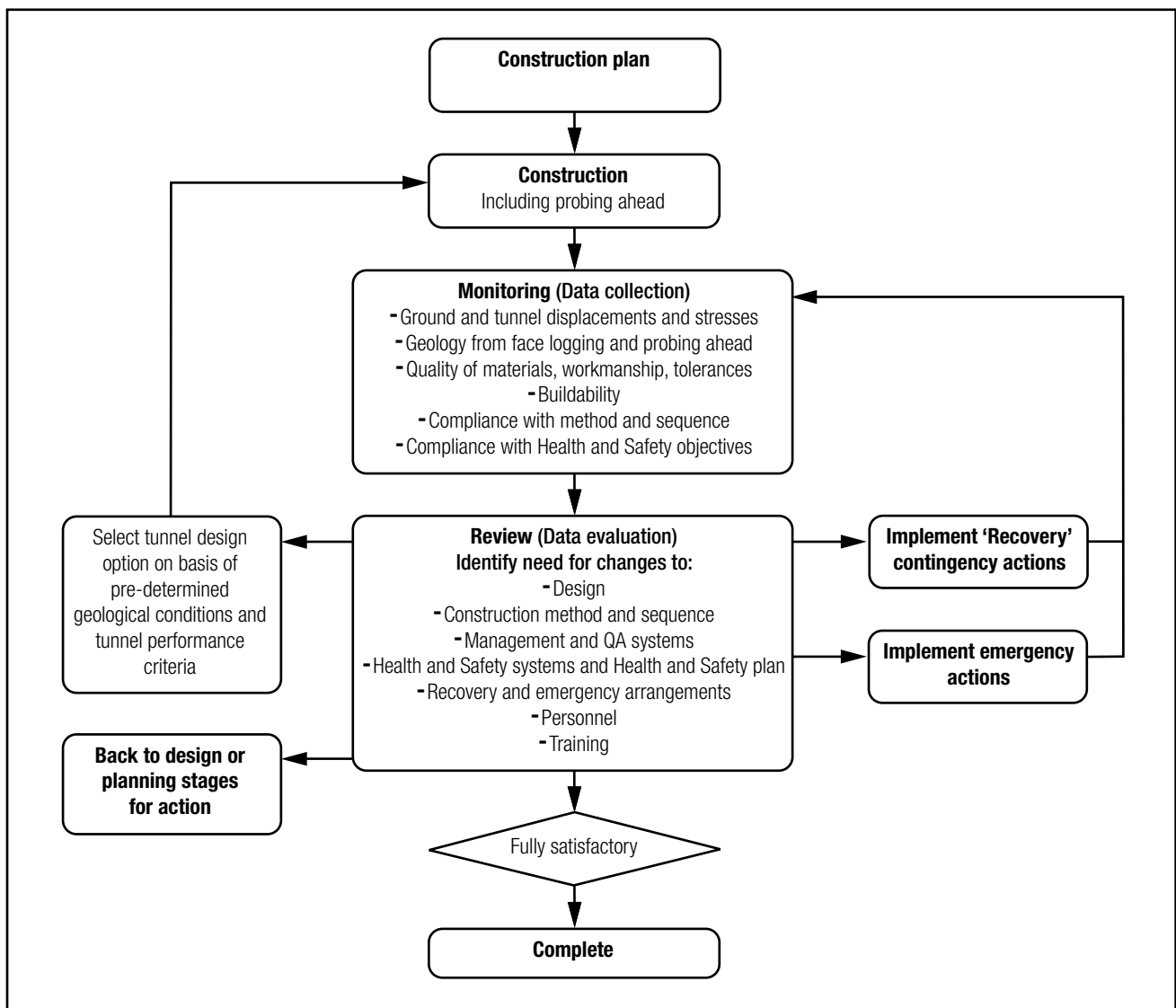


Figure 18 Monitoring and review during construction

267 There will normally be advantages in collecting and processing the data together and in joint reviews of behaviour. Data interpretation procedures must be established in advance so that confusion and delays in reaching safety critical decisions can be avoided. *Ad hoc* arrangements are inappropriate.

268 Interpretation is likely to involve several different disciplines within NATM teams. Regular formal meetings would constitute an appropriate way of managing the decisions. Those able to make a significant contribution could include:

- geological/geotechnical specialists;
- tunnel designers; and
- construction managers (including quality and safety managers).

Misunderstanding and errors will be reduced if the data available and decisions reached are formally recorded and distributed.

269 NATM monitoring produces a large amount of data. Management and timely processing is crucial to safety. Tunnel collapses have occurred where this has not happened and there has been insufficient time for contingency plans to be implemented. Monitoring data should be reviewed frequently to ensure that adverse trends and events are identified in time.

Application of the observational method

270 The observational method usually involves monitoring:

- the ground at and in front of the excavation face;
- surface settlement; and
- lining deformations.

In addition, ground water pressures, ground displacements and stresses remote from the tunnel may be measured. In some circumstances, loads in and against the lining are measured, but these may introduce significant problems with interpretation.

271 The variables to be monitored, and acceptable limits of variation, as well as appropriate contingency plans should have been specified in design. These plans will typically include:

- reducing the distance advanced with each excavation;
- reducing the size of the excavation faces;
- using thicker layers of sprayed concrete;
- early construction of secondary (inner) linings; or
- recasting lining sections.

272 Though designed to be robust, there are components of a NATM tunnel which are likely to become unstable with time. Monitoring should enable reliable estimates of their life expectancy. If the rate of deterioration has been determined in advance of construction and the tunnel is being appropriately monitored, the observational method should not introduce significant additional safety risks.

Design development and verification

273 Where design uncertainties have safety implications they should be verified. Design verification procedures, and the data required, should have been identified as part of the design studies.

274 Design development and verification may show that design modifications are desirable. These should only be necessary if unforeseen circumstances arise. Design modifications should only be used to enhance a robust design.

275 Design may be developed and verified using data obtained from construction trials. Trials require a rigorous approach to design and monitoring so that safety is not compromised. If the objectives are to resolve design uncertainties with safety implications, it is advisable to conduct trials in low risk locations.

Monitoring for failure mechanisms

276 It is inherent in the concept that robust designs are very unlikely to fail. However with current technology likelihood of failure cannot be discounted. Therefore there remains a need for monitoring to identify possible failure mechanisms.

277 When monitoring systems are designed reference should be made to the failure mechanisms identified in part 2. The manner in which they may develop should be considered in detail. Monitoring schemes should be based on thorough hazard analyses of all possible failure mechanisms, no matter how unlikely.

278 Rate of failure development must be reliably estimated. Planned contingency actions must be capable of completion before the level of risk becomes intolerable. This will require safety limits set at values below the onset of failure. Conservative estimates should be made of the time required to identify the need for and implement contingency actions.

Monitoring: tunnel lining

279 NATM tunnels may be constructed in close proximity to one another, e.g. the platform tunnels in an underground railway station. The effect of sequential tunnel construction on lining deformation should be considered when establishing the safety monitoring limits. This will involve complex engineering considerations so that a suitable safety margin remains at each stage of construction.

280 Similarly, if compensation grouting is being used as a settlement control measure, due allowance should be made for the deformations which may be induced in the lining (especially at the crown) by compensation grouting. The situation to avoid is one in which the security of buildings and services demands further grouting while tunnel stability can accept no more.

281 The manner in which the onset of failure is identified may vary depending upon project specific requirements. Normally, in modern NATM tunnels, safety monitoring can be achieved by using lining and ground deformation measurements. Deformation of a tunnel lining is dependent upon the interaction between the ground and the lining. This interaction is impossible to predict accurately, and the predicted deformations may not relate directly to the development of a failure mode in the tunnel lining.

282 In modern NATM tunnels in soft ground, the deformation of the sprayed concrete lining is normally measured by surveying the movement of reference points placed around the perimeter of the tunnel. The absolute movement is measured. A tunnel lining in soft ground can only fail if its length reduces so that locally the strain exceeds that which is allowable in the lining material. Monitoring should be designed to detect such developments.

283 In practice, the lining can be monitored by measuring changes in the length of chords around and across the tunnel. The allowable changes, i.e. those which cannot cause damage to the lining, should be estimated from the engineering properties of the lining.

Monitoring: tunnel excavation face

284 Face stability is crucial in avoiding the consequences of major failure and in securing worker safety. It is not generally possible to detect incipient failures as they can occur rapidly with little warning. Safety can be achieved through good design

and its implementation. Monitoring should ensure that design solutions are being followed and show no signs of distress. Monitoring should be undertaken by experienced and competent people.

Buildability

285 Buildability monitoring will show what elements of design are proving more difficult than anticipated. The objectives should be to:

- prevent divergence from agreed methods;
- reduce the level of variability arising during construction; and
- strengthen links in the team between designers and those carrying forward the work.

286 Buildability monitoring is best carried out in the early stages so that improvements can be incorporated at the earliest opportunity.

Compliance with specified methods and sequences

287 Checks should be made that safety critical elements of the design are being secured through the use of methods and construction sequences that have been specified by design and agreed between the parties.

288 These should focus on safety critical details of construction, such as the formation of joints, and larger issues such as following agreed build sequences in multi-tunnel construction. It is inappropriate for changes to come about in *ad hoc* ways through site practices. Any proposal for change needs to be agreed before use.

289 The monitoring of methods should not be limited to direct work activities. It should extend to general management, quality and monitoring systems that are in place. However, work activities may well have priority in the first instance since systems failures are generally more difficult to detect. Moreover, systems should add value and should be a means to an end (i.e. safe construction) through the support they provide to work activities. The way systems successfully target key issues, and provide readily comprehensible information of the right quality and on time to the right people, is one important measure.

290 Monitoring should target safety critical activities at an early stage. The level of informal review and more formally planned audits should flow from the quality plan. Importantly, this should be sufficiently flexible to recognise the possibility that the plan may not cover all eventualities. There should be the opportunity for additional monitoring where the need arises. The consequences of failure are too serious for investigative work to be constrained by an unhelpful system.

Quality

291 Once site work commences regular monitoring should be undertaken to confirm that quality standards are being achieved. This is considered at part 4.6.

Compliance with health and safety objectives

292 Strategic health and safety objectives set in the health and safety plan should be monitored as should activity specific objectives such as those for the safety of persons working close to faces. Both types of objectives should take full account of NATM specific issues.

5.5 Stability of the tunnel heading

293 The stability of the heading has implications for the safety of those within the tunnel, and for the safety of the public, buildings, structures and utilities above the tunnel. Most failures occur during or soon after excavation within the tunnel ahead

of the completed lining, (i.e. ahead of ring closure). This part of the tunnel is called the 'heading'. Heading stability involves the excavated faces, including any berms or nosings, and the incomplete linings. The latter are generally supported on temporary footings, (figure 3).

An outline of the soil mechanics applicable to heading construction in London clay

294 To reduce the load on the tunnel lining, modern tunnel construction uses the strength of the ground by controlling its movement into the excavation. As a result, the strength of the ground resists further movement and reduces the load on the lining. The strength of London clay varies significantly with strain. Initially, it increases rapidly to a maximum and then drops with further strain, at first rapidly and then more slowly, (figure 19).

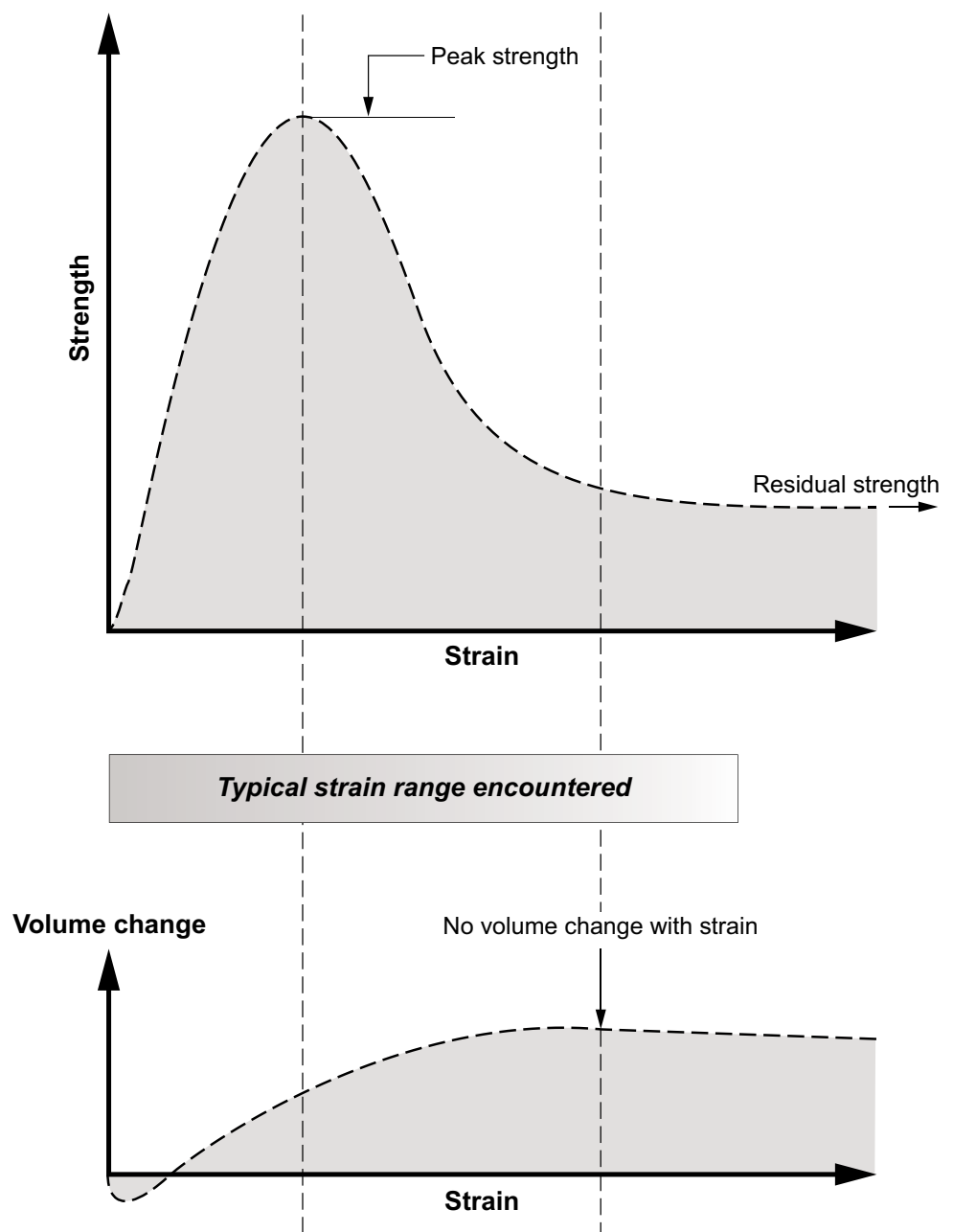


Figure 19 Strength of London clay

295 Under drained conditions in which the water in the pores of the clay can move, changes in its strength are normally accompanied by volume changes. Near a tunnel the strains induced by excavation will usually cause the London clay to dilate. These strains occur rapidly compared to the rate at which the water in the pores of the clay can move. Therefore, as water is nearly incompressible, the volume of the clay does not change significantly during construction of the heading. However, as a result of its tendency to dilate, the pore water pressures within the clay are reduced significantly. These pressure reductions increase the stability of the tunnel heading.

296 With time, water will be drawn into the zone of reduced pore water pressure and the clay will swell. The pore water pressure will rise, the stability of the heading will reduce, and further movement of the ground towards the tunnel will occur. Normally, these adverse changes will be reduced if the tunnel is advanced rapidly. (i.e. The faster the tunnel advances the more stable the face.)

297 In some ground conditions, typically deep rock tunnels, large strains may be required to fully mobilise the ground support. This may take several days, and if a tunnel lining is completed too soon unnecessarily high ground loads will be applied. This effect is not relevant in London clay, because, the strength of the ground is mobilised faster than the lining can be constructed.

The tunnel face

298 The sequence of excavation adopted for NATM tunnels usually requires steep temporary faces of height approximately equal to the heading diameters, (figure 1). Depending on heading size and ground strength, these faces have been left unsupported, covered by a layer of sprayed concrete, buttressed by a berm or nosing, or supported by some form of ground reinforcement or improvement.

299 London clay is not sufficiently strong to support excavated faces indefinitely and faces more than a few metres in height will fail. The face may stand unsupported for a short time and 'stand up' times of about 18 hours have been reported (Deane and Bassett, 1995). However this is dependent upon several factors some of which are difficult to evaluate.

300 Pore water pressure reductions required to prevent collapse of tunnel faces increase (i.e. become numerically larger) the greater the height and/or slope of the face, and the greater the initial pressures. The initial pore water pressure varies across the London Basin. In areas where grouting has been carried out shortly before tunnel excavation, it may be increased transiently, especially along fissures and silt or sand layers.

301 The rate at which water flows into the area of reduced water pressures depends upon the mass permeability of the ground. This varies with the stratification and the nature of the discontinuities near the tunnel. In London clay, the mass permeability measured by borehole tests varies widely.

302 Generally, the slopes of discontinuities within London clay are either near vertical or horizontal. This is favourable for heading stability. However inclined discontinuities do occur, and if large enough and unfavourably oriented, blocks of ground may fall into the tunnel. The 'stand up' time of these blocks may be short, especially if the surface of the discontinuity is soft (i.e. greasy backs). The likelihood of blocks falling from the face increases with the size of the heading. In the larger tunnels typically constructed by NATM, it may be expected that the incidence of falls will be correspondingly greater.

303 In practice, the 'stand up' time of unsupported faces in London clay is uncertain, may be negligible, and cannot be relied upon. For safety, 'stand up' times should be considered as 'fall down' time and conservative values must be considered.

304 NATM tunnels require a significant 'stand up' time so that the initial ground support can be erected. Normally, the 'stand up' time will only be sufficient if the ground is over consolidated and/or cemented. Typically, the first sign of instability is of blocks falling from the face. Though unlikely, a few blocks may indicate a general instability. If not controlled, failure of one block may be followed by others and the collapse may enlarge to form a hole in the crown.

305 Without water, the ground is likely to pile up in the heading and choke the crown hole. This will normally occur over a height of 2 to 3 tunnel diameters. However in the presence of water, the ground may be washed into the tunnel and the collapse may extend to the surface. Normally, a significant collapse of the heading will only occur if permeable water bearing ground is near to the tunnel. The risk of heading failures reaching the surface may be greatest when man made excavations or erosion features such as buried river channels are close to the tunnel.

306 If these conditions have been identified as a possible hazard then local investigations in front of the heading are likely to be necessary. These investigations are normally carried out by drilling near-horizontal boreholes ahead and slightly above the tunnel alignment. If permeable water bearing ground is found, special heading support measures, such as dewatering or ground freezing, may be necessary.

307 If a collapse occurs, emergency support may not be practicable with open faced tunnelling techniques such as NATM. Though support can be provided, there may not always be sufficient time to prevent a collapse. Closed faced tunnelling provides a readily available means of emergency support and reduces the risk. Therefore, proper ground investigation, heading design and construction are crucial to the safety of NATM.

Principal conclusion

Safety risks are greatest in tunnel headings. Open faces, a feature of NATM, are hazardous. Linings are more vulnerable to collapse before the ring is closed.

The incomplete lining

308 NATM involves a staged construction of the lining ring, (figure 1). The incomplete parts are kept close to the face and the load on them is reduced by support from the unexcavated material ahead. This support reduces as the distance to the face increases, and appears to become negligible at approximately 1 to 1.5 tunnel diameters.

309 It is usually practicable to design an incomplete lining that can support this reduced ground load. For tunnels in London clay, this may require the construction of special foundations to the crown arch, for example 'elephant's feet', (figure 3). However, if the width or the length of the heading is increased, substantial foundations may be required. Alternatively if the ground is weak, the size of the heading may have to be reduced. In extreme cases it may also be necessary to strengthen the ground before excavation.

310 Unless support has been provided before excavation, the ground near the front of the heading will be unsupported for a short time. If both the face and the previously constructed lining are stable, this ground will normally arch between them and significant ground failure is unlikely. However, relatively small blocks of ground may become unstable and fall into the excavation with sufficient energy to cause injury. Observation of the tunnel heading is unlikely to secure an acceptable level of safety. Special precautions should be taken, and no person should be allowed to approach the heading until all exposed ground has been supported.

311 A widely used precaution is to spray a layer of concrete onto the excavated surface from a safe distance, either with or without forepoles in the crown. If properly designed, this is safe, but the rate of gain of strength of the concrete layer, its thickness and geometry, and the ground loading should be carefully considered.

312 Safe places of work should be provided for those applying sprayed concrete. Mobile elevating platforms can be used to remove miners from areas of danger within the heading. To secure safety, both good working procedures and properly designed immediate ground support are essential.

Heading construction

313 For safety, the heading must always be stable. As safety cannot usually be achieved by monitoring the heading, every stage of its construction must be properly designed. Detailed drawings should be made to show the sequence of excavation and ground support. Calculations should be prepared to show the support mechanisms and confirm stability. The articulation and size of the construction plant should be considered so that, for example, the excavated surfaces and shape of the sprayed concrete linings shown on the drawings accurately represent those that will be constructed. The heading cannot be designed in detail until the construction plant and methods are known. Therefore, it is likely that the final heading design for a NATM tunnel will be carried out at the time of construction planning.

314 The heading design procedures should consider the basic mechanics of the ground. If pore water suction pressures are necessary for stability, the values used should allow for the flow of water towards the zone of reduced pressure. Also, they should be obtained by reliable means such as back analysis of a tunnel or by pore water pressure measurements. Due allowance should be made for local variations in the properties of the ground. If grouting is used, its possible effect on the pore water pressures should also be considered.

315 Safety will be enhanced if the heading is constructed rapidly and without error. Speed and quality are more likely to be achieved if construction is simple. Many of the techniques available to improve the stability of the heading also complicate and slow construction, for example:

- Reducing the size of the face by sub-division into galleries, or the use of pilot tunnels, may improve face stability. However, they may adversely restrict the choice and effectiveness of excavation plant and general working space.
- Galleries also increase the number of joints in the lining. Joints complicate construction and are potential sources of weakness. If galleries are used, the location of the additional joints and their construction should be given careful attention.
- Earth berms or nosings used to support the excavation face also restrict the working space available. Due to the risk of ground failure, narrow trench-like voids on either side of a nosing are not safe working places in which to construct the lining. They may also hinder and slow the spraying of the concrete.
- Berms cut to shallow slopes provide support to the face and reduce the likelihood of block falls, but they also increase the size of the heading and therefore the load to be carried by the incomplete lining. Usually, the time to complete the lining will increase with the size of the berm.
- Normally, face anchors and other forms of ground treatment used to achieve heading stability will slow down the rate of construction and significantly increase the time to complete the lining.

Principal conclusion

Monitoring is of limited value in the heading and does not ensure face stability. Therefore, every stage in the excavation of the heading and construction of the lining should be designed.

316 Well co-ordinated design and construction planning can probably achieve a reasonable compromise between the conflicting objectives of stability and ease of construction, and reduce the construction risks to as low as reasonably practicable.

317 The requirements for forward probing and geological logging of the ground in the heading, including the competence and safety of those doing it, should be considered during the design and construction planning. Safe access and adequate time should be provided for effective logging. This may significantly affect the rate of construction with adverse effect on safety and the form of ground support. Where extensive logging might be required for safety in a large diameter tunnel, pilot tunnels or galleries may be advantageous as the ground can then be logged before enlargement.

5.6 Ground settlement control measures

318 In urban areas, the control of surface settlement is necessary to prevent damage to the built environment above the tunnel. Settlement control may be achieved by several means such as:

- proper construction of the tunnel heading to reduce ground movements;
- under-pinning existing foundations (i.e. constructing new foundation supported below tunnel level); and
- compensation grouting.

Recently, the latter technique has been widely used for tunnels in London clay.

319 Compensation grouting is a technique used to control the settlement of the ground surface while a tunnel, not necessarily a NATM tunnel, is constructed below. The technique is derived from the established technique of compaction grouting in which grout is injected into the ground to counter surface settlement (Welsh and Rubright, 1994). In this technique, low slump grout is injected under high pressure and fractures the ground. The fractures are opened by the grout pressure and the ground surface is raised.

320 When a tunnel is constructed, the ground moves down towards the tunnel and the shear strength of the ground is mobilised to resist this movement. As a result, the vertical stress in the ground above the tunnel is reduced. Normally, grout can be injected into this zone using injection pressures which are less than they would have been if the vertical stress were undisturbed. The objective of compensation grouting is to prevent the development of significant settlement of the surface by injecting grout, at relatively low pressures, concurrently with tunnel construction. The process is a dynamic one with multiple injections of grout timed to coincide with the settlement trough induced by tunnelling, (figure 5). In this way a proportion of the ground displacement, which would otherwise have been transmitted to the surface as settlement, is taken up by a thin layer of grout.

321 Though the grout pressures used for compensation grouting are less than those in grout jacking, the pressures are still relatively large. Typical pressures required for grout injection in London clay are in the range 1 to 2 MPa (10 to 20 bars).

The pressures required to break out from the grouting tubes may be several times larger though typically this peak pressure is less than twice the injection pressure. Once injection stops, the pressure in the grout will drop but analysis of pressure readings taken during construction suggests that the excess pressure does not drop to zero. A significant residual grouting pressure in excess of the mean vertical stress appears to be sustained for several weeks at least. This pressure will create a zone of increased stress around the grout layer which, if the tunnel is nearby, may apply significant additional loading to the tunnel lining.

322 Based on field trials carried out in London, the residual pressure induced by grouting appears to be significant. However, it is not known how this pressure is related to the overburden pressure and to the break out resistance of the ground around the grout injection points. It seems advisable, until more data become available, to carry out trials and carefully instrument any tunnel lining near to compensation grouting to determine deflections and the induced additional loading. Unless the tunnel is close to the grout injection points, say within one tunnel diameter, the loading induced by compensation grouting on a tunnel lining is likely to be small. However, this load will probably be applied mainly to the upper part of the lining and act to increase the squatting deformation of the lining. The possibility of this additional lining deformation should be considered by the lining design. The effect at the face and on the incomplete lining within the tunnel heading may be significant.

323 In a saturated over-consolidated clay the stresses induced by grout injection will cause the pore water pressure in the clay to change. This change will depend upon many factors and may be positive or negative. Field trials show that the induced pore water pressures, both positive and negative, dissipate rapidly, returning to their pre-grouting values within a week or two. These increased pore water pressures may apply a short term additional load on the lining though this is unlikely to have a significant effect on the lining design. However, the field data are still limited and further tests over the full range may be necessary, especially where multiple tunnels are contemplated.

324 Excavations through London clay which have been treated by compensation grouting indicate that some of the grout fills natural fissures within the mass of the ground. If the clay is saturated before grouting, any water in these fissures will have been displaced by the grout. There are unconfirmed reports that when compensation grouting takes place near to a tunnel, the excavated face appears to become wet. These reports are difficult to verify but as they are consistent with a simple mechanism of ground water being displaced by grout, the possibility should be considered in design, especially in the assessment of the heading stability.

325 Proposals for activities to control settlement, such as compensation grouting, which may adversely affect tunnel construction must be evaluated and allowed for in the design. In addition to the effects on the tunnel under construction, the effect of compensation grouting on surface structures, buildings, utilities and nearby tunnels to be constructed later should be considered.

326 Compensation grouting should be taken into account in design. Its effects on the tunnel should be predicted to minimise risk. In stations and similar areas above sequentially constructed multiple tunnels in close proximity to one another there will be increased ground disturbance, higher ground loads on the lining, and larger settlement. This may lead to an increased demand for compensation grouting, hence an increase in the risk of tunnel collapse due to these effects. If compensation grouting is used, careful monitoring of the pore water pressures in the ground and the additional loads induced on the tunnel lining during construction would appear to be an essential risk control measure. (Note: This conclusion is applicable to all types of tunnel where compensation grouting is used and is not limited to NATM tunnels.)

327 In order to minimise the additional loading on the lining and reduce the potential rise in pore water pressures near the tunnel heading, an exclusion zone has been adopted on some projects. No compensation grouting is permitted within the exclusion zone, which is defined geometrically by reference to the tunnel heading. Typically grouting should not be permitted within one diameter of the excavation face nor within 3 metres of the completed sprayed concrete lining; but this should be determined on a case by case basis.

328 Information based on current monitoring should help to establish the feasibility of future schemes combining compensation grouting with NATM tunnels. The situation to avoid is one in which the security of buildings and services demands further grouting while tunnel stability can accept no more.

329 A further matter of importance is the effect that the use of settlement control measures such as compensation grouting can have on the safety culture of those working inside the tunnel. It is well known that care in construction and rigorous adherence to good working practices can reduce settlement at the surface. In the past, the high costs of structural repair resulting from settlement provided the incentive to follow best construction practices. With the advent of settlement control through other means, there may have been a commensurate reduction in the need to ensure best construction practice within the tunnel. The potential for an adverse change in safety culture, especially if senior management attention is directed more at the effectiveness of settlement control than construction quality, is clearly high.

5.7 Sprayed concrete lining design

330 A sprayed concrete lining acts as a thin flexible membrane that, compared with the ground, is stiff in hoop loading. There is a complex interaction between the lining and the ground in which the ground both loads and supports the lining. The lining relies upon the ground to prevent damaging deformation.

331 The modes of failure observed in sprayed concrete linings in NATM tunnels are summarised in the figures of failure mechanisms (table 3). In 'soft ground' direct transverse shear failure of the lining is unlikely as the ground around the shear plane will yield. Failure of the lining by bending is more likely. However, a collapse of the ground into the tunnel cannot occur unless there is loss of perimeter, i.e. the length of the lining must reduce locally.

332 A fundamental requirement of lining design is to keep the line of the hoop thrust close to the centre of the lining. In this way the extreme concrete stress is kept close to the average and most of the lining's load capacity is mobilised. For sprayed concrete linings with conventional dimensions, the concrete stress caused by the design hoop load is close to that allowable and relatively small amounts of ground movement may cause damage.

333 In practical terms the stiffness of a sprayed concrete lining will not significantly affect the deformation of the ground around the tunnel and, normally, the lining will deform with the ground. If this movement exceeds the strain capacity of the lining it will crack. To prevent a collapse, the lining must be able to support the hoop load as rotation occurs at the crack. If the strains induced by this rotation of the crack exceed the strain limit of the concrete, localised crushing will occur. If the crushed concrete is contained, which may be difficult to achieve, the loss of perimeter will be insignificant and the cracked lining may continue to support the hoop load. However, if the rotation causes 'wedges' of concrete to spall from the side of the lining, a progressive failure may occur with one side of the crack riding over the other.

334 Any compression failure of the lining is likely to reduce the length of the perimeter. The speed at which a collapse mechanism develops will depend on the type of ground and ground water regime around the tunnel, and in some circumstances failure may be rapid, i.e. a brittle failure may occur. A failure that develops rapidly may not be detected in time for contingency and emergency measures to be implemented. Therefore, for safety reasons, the sprayed concrete lining of a tunnel in soft ground should be designed to avoid brittle failure.

335 Compression failure of unreinforced concrete is a brittle mechanism that may unfortunately occur with little or no visible warning. In most circumstances, compression failure of a sprayed concrete lining will be caused by a combination of thrust and bending. Visible warning of an impending compression failure can be maximised by proportioning the lining so that it cracks in bending before it fails in compression. This may be achieved by adopting a conservative partial load factor on the hoop stress and a less conservative load factor on the stresses induced by bending, (i.e. by deformation).

336 Generally for NATM construction, this procedure will result in a lightly reinforced relatively thick sprayed concrete lining. Normally, a light mild steel reinforcing mesh is provided on both faces to contain any localised cracking and crushing. When the lining is deformed by the ground, cracks will open on the tension side and local crushing of the concrete will occur on the compression side. These may be visible if on the exposed surfaces. The conservative load factor on hoop stress ensures that the sprayed concrete lining, immediately after its effective thickness has been reduced by cracking and localised crushing, is still able to carry the actual hoop load. Hence visible warning of the impending failure may be provided.

337 Even when a robust lining has been designed there remains the need to plan for the possibility that the ground movement may strain the lining beyond its limit. If this occurs, the cracked lining may have to be removed and recast to the deformed shape.

338 Repairs and planned maintenance of a lining should be carried out by properly planned and designed procedures. This work requires careful risk management to secure continuing safety and *ad hoc* arrangements should be avoided. In general, repairs are made by removing thin strips of lining so that the unsupported ground can arch across the opening. This should be done while the adjacent lining has sufficient capacity to carry the additional ground load, and in time to allow any new sprayed concrete to gain sufficient strength. In all cases an analysis should be carried out to check that the adjacent lining can carry the additional loads and, if not, support should be provided. Normally, the lining should be repaired early and before any damage becomes extensive. Several stages of repair may be necessary.

339 Repair and discovery procedures depend upon prompt human action and introduce additional safety risks. These may be reduced by measuring the rate of development of lining deformations and comparing them with the allowable deformation. Then the timing of any necessary repairs can be predicted. Normally, this will significantly increase the time available for discovery and allow the repairs to be carried out before the lining is weakened.

340 Expanded segmental linings in London clay may be readily designed to permit deformation without damage. No equivalent detail is routinely available for a sprayed concrete lining and instead it would have to be repaired and recast to the deformed shape. Therefore, a sprayed concrete lining is inherently more susceptible to damage by ground movement than a segmental lining. Consequently, the prediction of changes in the shape of the tunnel periphery with time, and due to adjacent construction, is more critical to a NATM sprayed concrete lining.

Principal conclusion

The safety of completed sprayed concrete linings depends on monitoring and data interpretation. The design should determine the monitoring regime and contingency actions.

Deformation Analysis

341 The methods of analysis commonly used to predict ground deformations appear to fall into two groups:

- analytical methods in which the ground and lining are modelled as elastic/perfectly plastic materials; and
- finite element or similar numerical methods using more complex material models.

342 The assumption of elastic/perfectly plastic material behaviour used by the analytical methods is a major simplification of real material behaviour. Therefore, the methods are unlikely to provide precise predictions of actual behaviour. However they do provide bounds to possible behaviour and therefore they are useful design tools. In contrast, the numerical methods offer the possibility of modelling actual material behaviour and, at least theoretically, can provide good predictions of tunnel and lining deformations.

343 In a multi-variate problem, such as the numerical analysis of a tunnel in stiff clays, it will usually be possible to adapt the modelling procedure and input parameters to obtain an apparent agreement with a particular example, or set of similar examples, although the material model used is incorrect. However, such an analysis may not predict accurately the behaviour or another example in which the variables have changed. To have confidence in the prediction, it is necessary to independently confirm all significant variables and material models used in the analysis.

344 Most methods of analysis currently in use are based on two dimensional models of a cross section through the tunnel. A sprayed concrete lining is constructed in a tunnel heading while the excavation face is nearby. The deformation of the lining, and the stresses induced during construction, are significantly affected by changes along the length of the tunnel. Various two-dimensional modelling techniques, such as allowing the ground to close by a controlled amount before constructing the lining, have been used to estimate these three-dimensional effects. However, unless calibrated against reliable measurements of actual tunnel performance, the accuracy of these techniques is uncertain.

345 To provide a reliable prediction of the deformed shape of a sprayed lining to a NATM tunnel in London clay, the analysis should meet the following criteria:

- The material models adopted to describe ground and sprayed concrete behaviour should have been reported in the refereed technical literature and shown by scientific experiment adequately to describe their engineering behaviour.
- Most parameter values used in the material models should be consistent with values measured independently by laboratory or field tests. Where values obtained from back analysis of construction are necessary, the values adopted should be justified by reference to several projects in which the circumstances are similar.
- The analysis procedure must be specified clearly and should include modelling the initial ground stresses and tunnel construction. The procedure should be validated by reference to several projects in which the circumstances are similar and/or by reference to equivalent laboratory models. If the analysis is carried out in two dimensions, the validation should include three-dimensional data.

- The verification and validation of the numerical analysis should comply with internationally accepted quality systems, (ref.101).

346 It is probable that these principles can only be satisfied by a three dimensional effective stress model that predicts, with reasonable accuracy, the pore water pressure changes caused by tunnel construction. The model should also include the non-linear dependence of the stiffness of London clay on strain.

347 If an analysis does not meet these conditions, then despite any apparent rigour, the predicted stresses and strains within the lining and surrounding ground should be treated with caution.

348 Most numerical analyses used in NATM tunnel design are two dimensional. Their main value is to identify likely modes of tunnel failure and to optimise the construction methods and sequences. The latter is particularly valuable when multiple tunnels and/or shafts are to be constructed in close proximity.

349 In view of the uncertainties, a robust lining cannot be designed solely by analysis. To achieve a robust design, a strategy should be developed that properly considers the risks and uncertainties and incorporates knowledge of the behaviour of previously constructed tunnel linings, in particular their deformation.

Construction

350 During design, detailed consideration should be given to the practical difficulties of constructing NATM linings so that they may be satisfactory from the start of construction. If safety is to be assured, there is no opportunity for a 'learning curve' to bring the lining construction to a satisfactory standard. NATM requires the on-site formation of a high quality concrete based product under difficult site conditions. This can be contrasted with alternative forms of construction where high quality factory made elements (e.g. tunnel segments) are merely assembled on site.

351 The shape of the sprayed concrete lining is important. A circular or near circular cross-section reduces the risk of overloading. Particular care should be taken to avoid excessive flattening of the invert.

352 The means of forming the correct lining shape should be considered as part of the detailed design. The articulation of excavation plant, the means of profile checking, and the use of arches, are among the issues to consider. A shape that can be formed by excavation plant without hand cutting will speed progress and avoid putting miners at unnecessary risk near the tunnel face. Profile checks can be difficult to achieve in tunnelling environment and fully circumferential arches may help, especially where there are complex shapes to form.

353 The thickness of lining is crucial to its performance. Thickness control may be helped by specifying high visibility pins rather than leaving it to ad hoc methods, such as short lengths of reinforcing bars, which are unlikely to be adequate. Circumferential arches provide some guidance and this can be enhanced by specifying cover indicators at regular intervals along their inner faces.

354 The means of securing mesh reinforcement so that it is incorporated into the lining in the correct position should be specified. Purpose-supplied spacers may be more likely to achieve this compared to ad hoc methods. Fully circumferential arches provide ready fixing points.

355 The sequence for applying two or more layers of sprayed concrete to various panels to build up lining thickness should be specified. The means of cleaning and preparing the face of sprayed concrete before application of another layer should be specified so that satisfactory bonding is achieved and delamination avoided. The

specification for the application of sprayed concrete and, in particular, the control and removal of rebound material should be subject to particular review.

356 The design of joints in the lining should receive special care. Issues for consideration include:

- their position, (joints in invert are best avoided);
- shaping of the excavation close to joints to avoid 'necking' in the lining. (Stop-end boards or other visual indicators may be specified);
- construction of 'elephant's feet' or any other temporary support to the crown arch;
- installation of mesh and bars to provide continuity of reinforcement through the joint;
- cleaning and preparing existing sprayed concrete faces and reinforcement in the joint; and
- demolition of temporary linings (e.g. gallery walls and temporary invert) in multi-gallery work. Methods should be specified that reduce the likelihood of damage to the lining that is to remain.

357 A suitable working environment should be specified to ease construction and monitoring. A high standard of lighting and local exhaust ventilation are key factors.

Materials and components

358 The lining can be considered as a finished product made from materials and pre-fabricated components. Design and construction should take account of the issues surrounding their provision and use. 'Buildability' reviews may need to take account of sourcing, delivery, storage, on-site handling, and ease of incorporation so as to secure satisfactory construction.

359 Shotcrete specifications should be reviewed to ensure that the full range of options (for instance, wet or dry mixes, the incorporation of fibre-reinforcement, the early rate of strength gain, and mix designs,) have been considered so that the highest degree of certainty in the quality and the timely strength of the finished product can be secured. Additives which are aggressively harmful to people should be avoided. Likewise, build quality may be at risk from increased worker stress where aggressive additives and other hazards require the extended use of personal protective equipment.

360 The specification for the delivery of suitable shotcrete on demand to the shotcrete nozzle is a key requirement if faces are to be properly supported. Specifications should ensure sufficient material is stockpiled to provide for its ready availability. Issues concerning alternative shotcrete mix designs in the event that alternative sources of materials become necessary should be resolved where there is any doubt. The specification of the plant for mixing and delivery systems should be such as to secure a guaranteed flow of suitable quality and volume at the face whenever required. A specification requiring a planned approach to maintenance is more likely to avoid breakdowns. Back-up plant may be required; and the specification should take this into account.

361 Similar considerations concerning the security of sufficient and suitable supply are equally applicable to ribs, mesh and the many of other items that are required to support the face, to take lining construction forward, and to deal with the needs of planned recovery and emergency situations.

Part 6 - Management arrangements

6.0 Introduction

362 Effective management is central to the successful delivery of any project. This is true whether considering the objectives of clients, their advisers or contractors. Each party will have differing objectives in what they hope to gain from the project. For instance, each is likely to have an independent view of their commercial objectives. However, health and safety is one issue where all have a common interest.

363 HSE's booklet, 'Successful Health and Safety Management' – HS(G)65 – (ref 42) provides general advice. This part of the review considers how health and safety obligations can be fulfilled through management and, in particular, through a risk-based approach to the elimination or control of hazards in a NATM project.

364 NATM tunnels can be constructed without major incident as witnessed by those that have been successfully completed. Where failures have occurred, the literature suggests that poor management has been a significant contributory factor. Although NATM may be complex and technically demanding, it does not require skills not already available in the UK. However, these skills must be mobilised and effectively deployed. Competency is a central issue and here the client has a major role to play.

365 NATM is likely to be part of a larger project such as an underground railway. While it may be a small part of the project, it should, nevertheless, always receive the management and technical resources commensurate with the risks.

366 A distinctive aspect of tunnel construction is the integration of process and product safety. The planning, design and construction of NATM is highly complex and may last over many years. It will require many different disciplines to work together to achieve a satisfactory conclusion. Clear policies and firm direction are therefore essential from the outset so that all those working on the project clearly understand the set objectives.

367 NATM introduces four significant and interwoven issues. While not unique to NATM, they necessarily shape and influence the approach taken. These issues are:

- the management of uncertainty;
- the observational method and the crucial part that safety monitoring plays;
- the importance of achieving quality during construction; and
- the risks that human failings pose to safe completion.

The management of uncertainty

368 Any project brings with it a degree of uncertainty. For instance, tunnelling by whatever method, has a degree of uncertainty in terms of the geotechnical engineering. Uncertainty can be more accurately assessed where there has been previous tunnelling in similar ground using similar design and construction techniques.

369 However, where a technique is adopted for the first time in a different type of ground or people are otherwise unfamiliar with it, there will inevitably be greater uncertainty that will need to be managed. NATM is currently such a technique in the UK. This calls for high quality management by all parties and a risk-based approach that:

- recognises the uncertainties that may be present;
- eliminates uncertainty where that is possible;
- minimises the degree of uncertainty where it is not; and
- devises systems for successfully managing the residual uncertainties.

Principal conclusion

There is always some degree of uncertainty in tunnelling design and construction. This can be significant with NATM. A risk-based approach to design and management is required.

The observational method

370 Securing safety through the observational method requires a recognition of the processes that arise and of the management systems that are required. In brief, there must be management systems that:

- define acceptable performance limits for the purposes of safety;
- devise monitoring strategies which are able sufficiently early to detect adverse events;
- develop contingency and emergency arrangements which are capable of successful implementation; and
- put them into effect should the need arise.

Quality

371 The quality achieved in forming thin shell linings using 'open-face' techniques under arduous tunnelling environments is central to delivering product safety. How this can be satisfactorily delivered is a fundamental issue for the client, designer and constructor separately and severally to resolve. The elimination of unnecessary difficulty through good engineering design and the use of management systems that successfully deal with residual issues during construction is crucial.

Human factors

372 Managing uncertainty and the observational method introduce a high degree of reliance on the satisfactory performance of people. The importance of human factors to the safe completion of projects must therefore be recognised. Crucially, steps should be taken to minimise the opportunity for human failure and successfully to manage those critical safety events that rely on people.

6.1 A Risk-based control strategy

373 A risk-based control strategy should be adopted for NATM. Skills required for the construction of NATM tunnels should be acquired prior to construction. If people are not cognisant of the hazards and risks, there will inevitably be high levels of uncertainty and potential error in vital decision-making processes.

374 A risk-based approach to the management of a NATM project at large means that hazards and risks should be taken into account from a project's inception. This must include the possibility of 'high consequence – low probability' events. It should not simply focus on routine risks arising from work activities. The benefits gained by

involving experienced principal contractors at an early stage in this process should be carefully considered. As many of the safety risks have major commercial consequences, risk assessments are likely to be desirable for commercial as well as health and safety reasons.

375 A key issue is the assembly of sufficient knowledge. This should extend to:

- the legal duties which help focus the objectives to be achieved;
- the environment in which it is proposed to carry out the project; and
- the NATM process, and the means of achieving good engineering design and build quality.

376 Hazards can then more readily be identified, and uncertainties and risks either avoided or, where that is not possible, reduced to acceptable levels.

377 Wide consultation should be undertaken involving:

- client teams and advisers;
- designers;
- contractors (including specialists);
- others able to contribute towards the successful completion of the project; and
- those who may be affected.

378 Positive steps should be taken to develop close working arrangements at an early stage. The health and safety plan provided to prospective principal contractors prior to appointment is one means of passing on information about identified hazards and residual risks at a key step in a project's development.

379 Constructors should continue to focus on a risk-based approach specific to NATM so that management resources can be effectively deployed. The time taken properly to plan for a major NATM project should not be underestimated.

Principal conclusion

NATM tunnels require the deployment of considerable skill and care in investigation, planning, design, construction and monitoring. Clients, designers and constructors should not underestimate the complexity of the task they will face before and during construction.

6.2 Structuring teams and organisations

380 The complexity of major projects involving NATM is likely to result in each duty holder having a substantial management team. Individual team structures may not always be readily compatible with others. This can hinder communication, co-ordination, control and co-operation both within and between the teams. It can lead to uncertainties and human errors. A key safety point is to ensure that organisations are capable of securing safety in the light of the challenges faced by the project. This task involves all duty holders, clients and their advisers, designers, planning supervisors and principal and other construction contractors. Each should ensure that their own management structures enable them to address safety. The client can usefully take the lead in this. There is merit in including details of the client teams' proposals in pre-tender plans. These can inform principal contractors when they develop health and safety plans for the construction phase.

381 There are many ways in which the contractual framework can affect management and organisational arrangements. For instance, the difficulties of co-operation and communication are likely to be exacerbated the more complex the contractual relationships become and the more sub-divided the work. The policy should be to establish a framework which enables an integrated approach to safety critical issues.

382 Where a NATM tunnelling solution is likely, the issue of design co-ordination should be given prominence. For example the NATM lining, the face support and settlement control measures should not be considered other than as an integrated design.

383 It is important to ensure that safety critical parts of organisations are functioning satisfactorily from the outset. The more complex the contract arrangements the greater will be the effort required to ensure this; for example, difficulties of communication and co-operation may arise when major elements of the planning, design and construction process are contracted out to several different organisations. Continuous 24 hour construction requires the timely availability of senior management support for safety critical disciplines wherever there is the potential for an unsafe condition rapidly to develop. They may need to take command of contingency and emergency actions. The added difficulties in communications and command brought about by shift working patterns should be recognised and addressed. Uncertainties should be minimised by setting clear lines of accountability and liaison. Work patterns should be determined so that shift teams are equally integrated into management systems and so that out-going and in-coming teams effectively liaise.

384 Duty holders should co-operate so that they are jointly able to deal with safety critical issues. They should bring to bear the right people at the right times. They should have the information they need so that they can reach appropriate and timely conclusions about the way forward.

385 Contacts will be required at all levels of the various organisations so that safety critical issues are kept under proper and appropriate levels of control. This should involve those at the workplace (e.g. works inspectors) as well as those with overall control of project teams. Co-operation should cross disciplinary boundaries to ensure that necessary skills are deployed in decision-making processes. It should encompass design, planning, operational, quality control and health and safety personnel where they have a safety critical part to play.

386 Human factors may call for systems of independent review so that errors on the part of a single person do not give rise to unacceptable risk. Checks and balances in systems are helpful. Checks are exemplified by peer review and by senior management scrutiny of key performance indicators. Balances are exemplified by separating the construction, quality control and monitoring functions.

6.3 Project procurement

Introduction

387 Persons arranging for others to carry out work must ensure that there are adequate resources and competencies for health and safety. In practice this cannot be done without first identifying the risks. The consequences of failure call for rigorous checks before appointments are made.

388 Clients, especially for large projects, have a pivotal position. They can have considerable influence over the success, or otherwise, of NATM construction through the way they deal with letting contracts for design, construction and on-site monitoring and supervision; and the way they contribute to the design process.

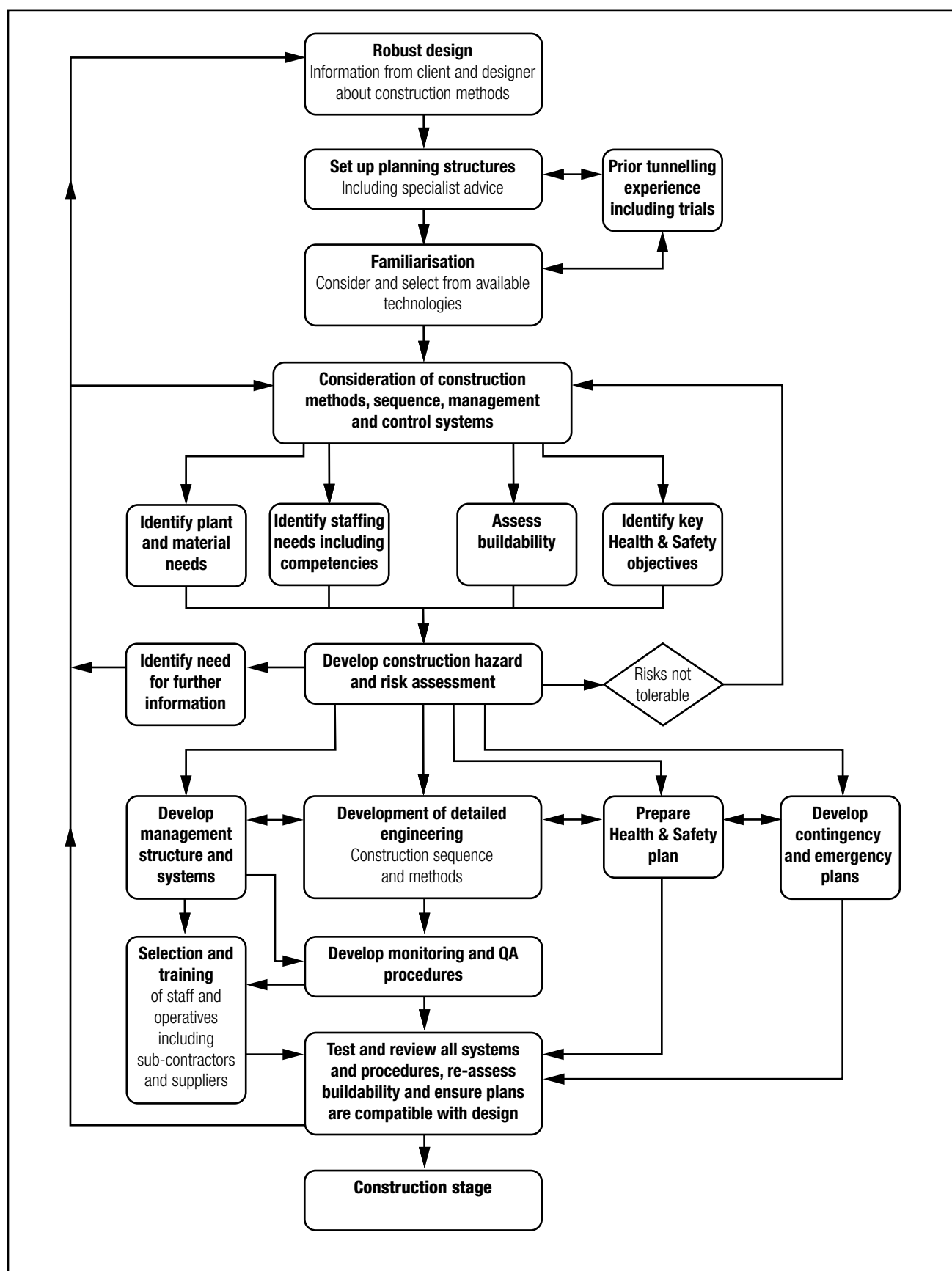


Figure 20 Construction planning

Contractual arrangements

389 There are many possible procurement models for a NATM tunnelling contract and various titles can attach to the parties. None is endorsed as the best in safety terms. Some contractual arrangements, divide design work between designers appointed by constructor and lead-designers appointed by clients. This typically occurs when the NATM lining design is constructor-led, as an element of 'temporary works'. This may inhibit the development of an integrated design approach. The crucial point is that contractual arrangements should take full account of the advice in this review on the functions of design, construction, monitoring and supervision; and for the need for the closest co-ordination between them. It is essential that there is a full understanding of the relationships that will be created between the various parties so that potential difficulties for securing co-operation and communication can be avoided. Clients unfamiliar with such issues are advised not to proceed without first obtaining expert advice.

Engineering Design

390 Design and construction, including on-site monitoring, are closely intertwined in tunnelling projects. Difficulties may arise if this is not recognised in the way contracts for services and construction are let. The design function requires particular mention. NATM is an interactive process that intimately binds together the design of the permanent and temporary works.

391 Design develops within a multitude of constraints, in particular, the available technology; and it has to take on board health and safety issues. Design will extend through the construction phase because of the uncertainties that have to be addressed and the consequent need to monitor the performance of the works during construction.

392 Traditionally in the UK, the client has appointed an engineer to fulfil the design and monitoring function. Modern practice has been increasingly to divide these functions. This may lead to issues that are better taken together being considered separately and may inhibit the development of designs which minimise risk. Procurement should take this into account.

Principal conclusion

Competency of the NATM team is crucial and should be assessed.

6.4 Project planning and outline design

393 Health and safety risks associated with NATM tunnel construction are significantly affected by the planning and outline design stages of projects (figure 20). Due consideration should be given to risks early in design so that they may be reduced.

394 The purposes and routes of tunnels will be determined during project identification or feasibility design stages. Environmental, planning, political and economic considerations may be to the fore, but high consequence safety issues should also be considered. At this stage, it may be that only general indications of tunnel construction methods will be available, sufficient to establish technical feasibility and probable costs but insufficient wholly to address safety issues.

395 As planning and design are developed from feasibility through to detailed design, planning supervisors, in conjunction with the designers and clients, must identify the principal health and safety hazards. Other matters may significantly affect the cost or feasibility of the construction works, but they are not part of

health and safety assessments if they are not relevant to it. For example, a tunnel may cause settlement of overlying buildings and structures and may be of economic concern, but this may not create safety hazards. However, settlement of some structures, such as railway viaducts and tunnels or utilities such as gas mains, may result in both economic and safety hazards.

396 Significant health and safety risks associated with all construction methods likely to be used on a project should be identified and reduced to acceptable levels at early design stages. Some proposals (e.g. tunnelling in less satisfactory ground) introduce additional health and safety hazards. It may be possible to reduce or even eliminate them early in the design process by, for example, changing the longitudinal profile of the tunnel. Designers need to provide sufficient relevant information about the totality of the design, including the construction and safety monitoring that is necessary.

397 Health and safety design reviews should follow hazard identification. Reviews should actively involve designers; the planning supervisor; and construction contractors if appropriate, associated with the project. They should identify the options available to reduce significant health and safety risks. The options considered may include:

- alternative tunnel routes in plan, level and profile;
- additional ground investigation;
- adjustments to internal tunnel geometries;
- changes to proposed construction programmes;
- varying the number and locations of shafts and portals;
- alternative tunnelling methods; and
- reviewing settlement control measures.

398 Special attention should be paid to avoiding 'low probability' but potentially 'high consequence' events, especially where they involve significant hazards to the public.

399 People exercising high level design functions should consider whether any hazard identified by one designer has health and safety implications for another. For instance, use of compensation grouting above a tunnel to control settlement may have implications for lining design. Planning supervisors should co-ordinate health and safety aspects of the two designs.

400 Planning supervisors should start project health and safety plans towards the end of the conceptual design stage, if not already done. When completed, the plans should contain adequate information on health and safety for potential principal contractors. Plans could include:

- results of conceptual design health and safety reviews;
- data about significant hazards which have been identified; and
- ground investigation data and geological interpretation.

Principal conclusion

There will be locations where the consequences of collapse are unacceptable. In such cases alternative solutions should be adopted.

6.5 Selecting tunnelling methods

401 Tunnelling methods should be selected so that adequate regard is given to avoiding hazards and combating at source foreseeable risks to those carrying out the work and others who may be affected.

402 There may be special circumstances which favour the specification of a particular form of tunnel construction. There may also be circumstances in which it is appropriate for the tunnel designer to specify particular aspects of the sequence of construction.

403 Closely juxtaposed multi-tunnel layouts require particular scrutiny. Only after considering the alternatives should a choice of construction method be made.

404 If NATM is a possibility, the particular advantages and disadvantages should be considered. Proponents claim that NATM can:

- reduce the cost of tunnelling;
- offer the opportunity for a wider range of tunnel shapes;
- permit the construction of closely juxtaposed and large span tunnels by early formation of common walls and foundations;
- be adapted to suit wide ranges of ground conditions;
- adapt to changes in tunnel shape without significant changes to plant, materials or working methods;
- make use of readily available, and reusable, plant and equipment.

405 However, there are a number of possible safety disadvantages to NATM. These include:

- increased risk of face instability due to lack of face support;
- greater difficulties in maintaining quality control of in-situ linings and ground support;
- increased risks of lining damage and ground collapse due to difficulties in predicting stresses and strains within linings;
- heavy reliance on monitoring and analysis to avoid tunnel collapses;
- greater vulnerability to human failures; and
- greater potential for face instability in the event of reductions in the advance rate.

406 In the range of ground conditions where NATM is normally used, alternative methods are available and should be considered. These include:

- hand mining (using face support with faces closely boarded during intermissions);
- shields with or without road headers;
- mechanical shields (i.e. tunnel boring machines (TBMs)); or
- closed face TBMs which support the ground by face pressure.

407 Hand mining uses timber face boards and walings kept readily to hand to support faces; open shields may have face rams with sliding tables or spreaders; TBMs may have means for partial face closure; while pressure-balancing machines depend on rigorous pressure control to ensure continuous support. The common feature in soft ground is some form of completed lining close to the face which provides support for strutting or face pressure.

408 The extent to which these tunnelling methods lend themselves to non-circular geometry varies considerably. Hand mining is very flexible. Tunnel shields may be given an elliptical profile, but this more difficult and seldom worthwhile for TBMs.

Hence TBMs are generally used for long lengths of uniform cross section (e.g. running tunnels between stations), shields are used for medium lengths of uniform cross section tunnel (e.g. cross over junctions and station tunnels) and hand mining for short or geometrically complex sections (e.g. local enlargements, platform cross connections, step plate junctions). Shields and TBMs require shield chambers within which they can be erected and possibly dismantled. These may be constructed using NATM or by timbering.

409 These alternative tunnelling methods normally use off-site manufactured lining segments. Better quality control can generally be achieved than on site and faulty segments can be discarded at any time before use. One technical advantage of well designed segmental lining is their ability to rotate at joints and accommodate some unexpected ground deformations without damage.

410 On some projects several different excavation techniques may be used separately and jointly to secure quality, economy, speed of construction and safety. For instance, TBMs may be used to form running and platform tunnels of uniform cross-section. NATM might then be used to widen what is in effect a large pilot tunnel. This approach provides the opportunity for close geological survey prior to NATM work.

411 If construction contractors submit NATM options that have not been considered by lead designers significant problems can arise. The opportunities for developing safe integrated designs may well be lost. As well as delays, there may also be considerable difficulties in co-ordinating temporary and permanent works designs. Alternative design options should not be accepted without careful review involving designers and planning supervisors.

412 Final decisions on tunnelling methods should take into account health and safety as well as construction costs. Account should be taken of the probability of tunnel failure, particularly in urban areas, and of the very serious consequences that could result. Any apparent initial saving from adopting more hazardous methods could well be exceeded by the additional costs of risk management control measures and failure.

Principal conclusion

An integrated approach should be taken to the design of permanent and temporary works. Design should consider the whole process of NATM tunnel construction.

6.6 The design/construction interface

413 Successful management of the interface between NATM design and construction is essential for safety. It is necessary that all parties appreciate this. Just as constructors should take a keen interest in and understand design, so designers should take a keen interest in the problems designs may pose for constructors. Buildability requires close co-operation between constructors and designers if it is to be satisfactorily addressed and risk minimised. It is one example where design affects safe construction.

414 The converse is also true, construction affects design. In common with other types of civil engineering construction, especially those with substantial elements of ground engineering, construction methods and sequences have a significant effect on the performance of the completed works. Determining construction methods is

a fundamental part of design and, for successful outcomes, close liaison between NATM designers and construction management is necessary. For example, the main design value affected by NATM construction methods is the strain, and hence the shear strength mobilised in the ground around tunnels during excavation and lining construction. Ground strain is largely dependent on construction methods and the speeds achieved.

415 The interface between construction and design is further complicated by using the observational method. Monitoring results, obtained as work progresses, are required to confirm lining design and construction methods. If design modifications are required, NATM designers must be closely involved during construction and monitoring. Interfaces between NATM designers and constructors should be managed carefully to ensure that the objectives of both the design and construction teams are achieved.

416 Design co-ordination should be to the fore where NATM is proposed because of the wide ranging safety implications. It is clearly preferable for comprehensive design solutions to evolve from design processes where the implications for all the permanent and temporary works have been fully considered. For example, if the presumption of a NATM based solution has been made at an early stage in the design process and not further considered, or not considered at all, until the post-construction tender appointment of a NATM designer, there may be fundamental issues with wide-ranging implications to address against a background of limited knowledge, pressures of limited time and resources already expended on tunnel design. Similarly, temporary works design for stability of excavated working faces needs to be integrated into other designs for the permanent and temporary works and for settlement control. Design of settlement control measures will need to be integrated into NATM design work to ensure that unacceptable risks are not introduced.

417 There should preferably be a continuity in the design process, extending through the construction period, to ensure that the special requirements for NATM are considered at all stages. This could involve all parties to the project depending on the particular circumstances.

418 Though predominantly the concern of principal contractors, clients may also be directly involved in the construction stage because of risks to other people as a consequence of the project. Clients may have their own supervisory teams to ensure build quality and the proper implementation of designs or they may rely on advisers.

419 Similarly, planning supervisors have a role at the interface in advising clients, if asked, about health and safety plans prepared before commencing construction work. They should be capable of advising about project management structures and the procedures necessary for health and safety. They may have a part to play during construction in dealing with on-going design work. This is particularly important when NATM designers are appointed at a time when other design is well advanced, e.g. when designers are appointed by principal contractors.

Principal conclusion

‘Buildability’ (ease of construction) should be considered in design and construction planning.

6.7 The construction stage

420 The adoption of NATM-based tunnelling solutions has significant implications for the number and quality of managers, engineers and operatives required on site. It is a resource intensive process which cannot be ventured upon lightly if safety is to be secured. It is crucial that there is sufficient understanding of the issues which arise during construction when NATM is postulated. A risk-based control strategy should be adopted.

421 Any limitations imposed by designs on construction sequences and programmes must be clearly understood. Safe working methods and contingency and emergency plans should be developed. Suitable management structures and systems should be determined to deal with the residual risks. These, and other matters, should be integrated into health and safety plans developed for the construction phase.

422 Widely drawn consultation extending to client teams and advisers, designers, contractors and others who may be affected or able to contribute towards the successful completion of the project is appropriate.

423 Project planning by principal contractors will have commenced to some degree during tendering periods. Whilst legal duties do not apply to principal contractors until they are appointed, there is clearly much that can usefully be done pre-award to ensure that the project can satisfactorily be carried forward (e.g. considering appointments of other contractors and contractor-led designers, and health and safety planning). Indeed, the financial risk of not doing so could be substantial. Tentative appointments of specialist designers, whether during a tender period or thereafter, should be preceded by enquiries about their competencies and resources. Further advice about the enquiries which should be made is given in the Approved Code of Practice (ACOP) to the Construction (Design and Management) Regulations 1994 (CDM).

424 Account should be taken of the availability of knowledgeable, competent and experienced suppliers (whether of raw materials, components, or plant), contractors, managers, engineers and other work people so that suitably qualified teams can be mobilised. Necessary competencies will need to be determined. Training programmes will need to be devised. Specialist support skills, such as health and safety advisers, should be subject to similar scrutiny so that they will be able to play their part during the project. Those assembling teams to carry out supervisory roles (e.g. client teams) will need to pursue similar issues.

425 A range of information should already be to hand about the physical environment. However, it may not be sufficient for the particular methods a contractor wishes to adopt. For instance, there may be a need further to investigate what structures and infrastructure could be at risk in order to determine what can be done to protect people in the event that they are placed at risk. Means of liaison and advice to others off-site in the event it becomes necessary to implement emergency plans will require investigation.

426 NATM construction requires a focus on the key issues that secure safety. It merits separate consideration in health and safety plans. They should address the risk management issues raised by this review. The concept of the 'discovery-recovery' model and the way that monitoring, review and planned contingency and emergency actions will be dealt with requires particular mention. The close integration of other parties necessary for successful completion will need to be addressed in terms of the arrangements for communication, liaison and joint

reviews. The means of providing information about NATM to employees and in opening up discussion with them towards the safe completion of NATM should be addressed.

427 Although this review deals with major safety hazards created by NATM process, other hazards will need to be taken into account. These include:

- health and health surveillance: particularly with respect to:
 - the handling and use of shotcrete and its additives;
 - local dust extraction at faces;
 - the control of exhaust fumes; and
 - general ventilation;
- manual handling;
- the provision and use of plant;
- safety in the use of transport;
- the provision and use of suitable access, egress and places of work;
- lighting;
- workplace layout;
- in-tunnel communications;
- general contingency and emergency procedures;
- welfare and first-aid facilities;
- site rules;
- control of contractors; and
- safety of others including the public.

6.8 Contingency plans and emergency procedures

428 Planning for emergencies underground has long been undertaken. NATM also requires the preparation of contingency plans so that action can be taken with the minimum of delay to remedy adverse developments. There will always be residual risks which cannot be eliminated and adequate procedures must be in place to ensure that people within the tunnel and elsewhere are protected. Procedures must be based on a thorough understanding of the hazards presented by NATM and take full account of the consequent risks. Procedures should be practicable in the difficult circumstances and working environment in which they may be deployed.

429 Risk assessments, based on fully understanding possible mechanisms, are precursors to the development of plans. Assessments should identify, describe and where possible, quantify the foreseeable risks. The consequences will depend on conditions specific to each tunnel. NATM tunnelling with large excavated faces may introduce higher risks of excessive settlement, face and lining collapse; particular attention must be paid to ensuring that these factors are fully addressed.

430 Risk assessments should identify foreseeable, even if remote, scenarios. The rate at which hazardous situations might develop should be considered. From such analyses, procedures should be developed which are capable of securing the safety of workers and the public.

431 Other NATM tunnelling hazards should be considered. These could include:

- collapses of shafts or other means of access;
- substantial ground movement likely to damage adjacent structures etc;
- serious delay in tunnel construction sequences;
- in-tunnel fires;
- inundation of tunnels or associated works;
- contamination of tunnel atmospheres;

- explosions including pressure vessel failures;
- failures of services in or adjacent to tunnels;
- evacuation of injured persons; and
- contaminated ground.

Contingency plans

432 The first aim of contingency plans should be to contain and correct any developing problem before it becomes critical. Many hazards are common to all tunnelling methods although the level of risk may vary. NATM introduces the potential for increased risk from lining failure, face collapse and excessive settlement.

433 It is important that measures to support tunnel linings and faces can be implemented quickly and effectively within the times likely to be available. To achieve this, potential scenarios should be analysed and remedial measures developed in advance. These should include the full design of support arrangements including proposed methods of installation. Procedures for remedial work should form part of contingency plans. Plant and materials should be close to hand and all initial support materials stored as close to the working face as is practicable. Where materials such as sprayed concrete are to be used, consideration should be given to the reliability of supply and the need for backup facilities.

Face Collapse

434 Most face collapses are likely to be limited in extent although they may still pose serious risks to miners. Where there is the potential for face collapses to progressively unravel to the surface, there may be risk to others, either directly or indirectly. Fully designed measures must be developed to ensure that failing faces can be quickly supported.

Lining failure

435 Warning or trigger levels for convergence should be developed from lining designs. These should give sufficient notice of developing problems that may lead to lining failure. Recovery measures should be sufficient to support the lining and prevent progressive failure. It may be necessary to design a range of measures to cater for different locations within a tunnel.

Excessive Settlement

436 Even in properly designed and constructed tunnels, settlement may be greater than overlying structures and services can accommodate and some engineering means may be necessary to control settlement. Risk analyses must take into account the possibility that settlement exceeds predictions for whatever reason. Monitoring should therefore be in place to ensure timely warning so that appropriate action can be taken. Face collapses and lining failures may result in excessive settlement above the tunnel and the emergency procedures should reflect this possibility.

Emergency Procedures

437 The first intention of emergency procedures should be to manage risks from developing incidents where control is apparently being lost. The prime objective is to secure the safety of people. Emergency plans, including above and below ground evacuation arrangements, should be in place throughout tunnel construction. There may be an initial need to ensure evacuation of non-essential personnel as quickly as possible from affected areas. There will be circumstances when emergency arrangements, including evacuation, may need to be implemented immediately. Arrangements must be in place to ensure that:

- all persons can be safely evacuated from areas at risk underground;
- all persons potentially at risk either elsewhere on the site or on the surface can be evacuated to places of safety;

- third parties, whose people, premises, plant or equipment may be at risk, are given sufficient warning to enable appropriate action to be taken; and
- emergency services can be quickly contacted.

438 Such arrangements can only be effective if they have been developed from analyses of the hazards and the likely consequences in consultation with all interested parties and the emergency services. The following are some of the essential features of any emergency plan:

- clear and simple arrangements for management and control;
- clear instructions;
- adequate training;
- adequate means of communication above and below ground to those affected and those dealing with the emergency including the emergency services;
- adequate emergency evacuation arrangements;
- a means of accounting for all people on site and in particular those underground;
- provision of appropriate emergency plant and equipment;
- agreed arrangements for emergency services including rendezvous points and supply of all relevant information;
- agreed arrangements for advising third parties, including service authorities, of developing situation and jointly agreed arrangements to control risks; and
- testing the arrangements by 'table top', full scale and other exercises as appropriate and a means of ensuring that plans are upgraded as a result of lessons learnt.

439 It is essential that full emergency procedures are set out in writing. As emergency situations can develop rapidly, plans must consider a realistic range of potential scenarios. Procedures should specify when and how planned stages should be activated. Procedures should set out the specific responsibilities persons nominated to implement detailed actions.

450 It is essential that the emergency plans are live documents that are kept under review as conditions and the nature of the tunnelling work will vary during the course of any project.

Principal conclusion

Contingency plans and emergency procedures are required to deal with adverse events.

Appendix 1

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Appendix 2

Health and Safety Executive Discussion Paper on the use of NATM in the UK (published 5th December 1994)

Introduction

After the partial collapse of the New Austrian Tunnelling Method (NATM) tunnel at Heathrow on 21st October a ministerial statement said the Health and Safety Executive (HSE) would investigate and also consider whether there were any broader implications for the use of NATM. It also said that HSE would review the evidence to establish whether, during construction, safety of tunnels using NATM matched that of more conventional techniques. At the same time HSE asked that the voluntary suspension of the NATM at Heathrow and Jubilee Line Extension Project (JLEP) should be maintained until it was clear that work can restart safely.

This paper serves two purposes:

- 1 It contains the emerging findings from HSE's discussions about current NATM projects in London, in order to indicate those issues which need to be addressed before NATM work restarts.
- 2 It is intended to invite other parties to contribute information to HSE's wider review of NATM.

These findings have emerged from HSE's consideration of all the current NATM projects in London and should not be construed as being critical of or passing comment on any current use of NATM. It is also entirely without prejudice to any HSE findings about the collapse at Heathrow.

Emerging Findings

Appendix 1 contains a list of the main issues to be addressed by those wishing to undertake NATM but some issues emerge as being of particular importance. These are as follows:

Contractual

- 1 Does the complexity of the contractual arrangements between clients, designers and constructors mitigate against successful health and safety management especially with a construction system which depends heavily on human factors through the use of observational techniques, to validate and/or guide modifications to the design during construction?

Client knowledge

- 2 Do clients have access to sufficient experience and expertise to enable them to evaluate and assess NATM design and construction issues?

Design and its implications

- 3 Has the design taken buildability into account and can the design be safely constructed? Does the design include adequate factors of safety?
- 4 Does the design adequately cater for complex multi-tunnel operations, cross passages etc and are details of necessary site construction sequence and control clearly defined?
- 5 Are procedures adequate for assessing the significance of any remedial works in relation to the design concept?

Ground conditions

6 Do the contractual arrangements, site management, instrumentation and emergency and contingency arrangements reflect the degree of knowledge of the behaviour of the ground, taking account of all construction work?

7 Are the assumptions made about ground conditions accurate and have the consequences of inaccuracies in comparative data especially in terms of ground condition modelling and ground settlement predictions and shotcrete lining load development been properly considered?

8 Does the design adequately take into account ground conditions and ground loadings arising from existing structures, and works, enabling works, and ground improvement works especially compensation grouting?

Site Management

9 Are the safety-critical features of the design fully appreciated by those on site, and are these features clear from the plans of work, method statements etc considering e.g. the criticality of the tunnel profile; the sequence of construction; areas of complexity where flexible and rigid construction abut?

10 Is the quality management of shotcrete strength, thickness etc adequate; is sufficient use being made of non-destructive methods to assist in targeting on potentially suspect areas; and are samples taken from e.g. invert or other places of interest done on a worst case basis i.e. highest stress points and anticipated locations of poorest shotcrete?

11 Are site management control and communication arrangements adequate and are there sufficient trained and competent staff available 24 hours a day?

12 Are emergency arrangements and contingency plans in place to deal with all potential failure scenarios based on a continuing evaluation of the work in progress?

Instrumentation and monitoring

13 Are the tunnel instrumentation and monitoring arrangements sufficient in relation to ground conditions, construction complexity, and sensitivity of design criteria, and are the results of monitoring interpreted with sufficient frequency, and in relation to prior estimates of expected instrument readings computed at each stage of construction? And is this information fed back to the design team for ongoing assessment in relation to both the design and construction procedures?

Action by Industry

The onus is on those who undertake work to ensure safety before NATM work restarts. They should ensure that the listed issues are addressed, but should not regard the list as exhaustive. Nor should the list restrict due consideration of issues which may be relevant to a specific project.

HSE in producing this paper hopes to inform and stimulate discussion in the industry about the use of NATM. It would like to hear from anyone who wishes to contribute to this debate. Anyone who responds to this request to provide information should do so on the basis that all or part of their submission may subsequently be published by HSE.

Comments should be sent to Andrew Maxey, Health and Safety Executive, Heathrow Investigation Project Team, 5th Floor North Wing, Rose Court, 2 Southwark Bridge, London SE1 9HS by 16th January 1995.

Appendix 1 [to Appendix 2]. List of Issues to be considered when assessing safety in the use of NATM

HSE would wish to see this list of issues considered by designers, constructors and others involved in NATM work, or any other similar observational tunnelling techniques although some of these issues may also apply to all tunnelling work. (The term NATM includes incremental tunnel excavations and shotcrete lining methods.) The purpose of this list is to inform those who undertake NATM work about the health and safety issues but it should not be regarded as an exhaustive list, nor should it inhibit proper and due consideration being given to other issues which may be relevant to a specific project.

1 Introduction

1.1 General description of the project and NATM proposals.

1.2 Particulars of any general technical specifications, standards or codes relevant to the project.

1.3 A clear description of how, taking into account the following issues, an integrated system of managing and controlling the risks arising from NATM and associated works will be implemented in practice.

Contractual, design and procurement issues

2 Overall criteria

2.1 Criteria used and explanation of the decision making process in selecting NATM evaluated against alternative excavation or lining techniques in terms of Health and Safety.

3 Geotechnical assessment

There should be a full geotechnical assessment to include:

3.1 desk studies;

3.2 ground investigation to determine:

- .1 ground conditions;
- .2 groundwater regime and fluctuations;
- .3 engineering properties of soils and rock relevant to anticipated construction and analysis and design techniques;
- .4 geological structure and fabric;
- .5 in-situ stress conditions; and
- .6 engineering parameters to enable temporary works design.

3.3 consideration of implications of variations in ground and groundwater conditions and soil and rock properties allied with sensitivity analyses;

3.4 consideration of the importance of in-situ stress conditions and how they may be altered by shaft sinking and tunnelling, especially multi-tunnelling operations.

4 Details of the overall project design and concepts:

4.1 a systematic approach to overall project design should be adopted which takes account of all relevant factors which could have an influence on it and be influenced by it;

4.2 key drawings, specifications and design calculations;

4.3 location plans especially survey details of other works and structures in the vicinity;

4.5 use of compensation grouting, or other ground improvement or remedial works; consideration of in-situ stresses in relation to behaviour of compensation grouting;

4.6 assessment of the extent to which the design is operating on frontiers of existing knowledge and experience re: technology; complexity; knowledge of ground conditions and their favourability or otherwise etc;

4.7 sequencing of work on multi-tunnel or other complex constructions;

4.8 verification of design parameters and design calculations with particular emphasis on verification and validation of numerical models/computer programs used in analysis and design.

5 Design and operability studies – both on and off site

5.1 hazard identification and analysis;

5.2 risk assessment:

.1 statement of the significant findings;

.2 take account of:

.1 limitations in ability to fully characterise the site ground conditions and potentially affected structures;

.2 limitations in ground – structure interaction analysis and prediction of structure responses to ground deformation

.3 limitations in analysis and design techniques

.4 industry experience in NATM design and construction

5.3 consequence analysis;

5.4 sensitivity analysis.

6 NATM design methodology

6.1 analysis and key design assumptions and overall design philosophy. (With reference to 'safety factors');

6.2 construction proposals including construction sequences and all working details;

6.3 observational methodology including methods for monitoring ground and lining conditions during construction;

6.4 safety critical factors;

6.5 working procedures;

6.6 detailed method statements and systems for ensuring compliance;

6.7 consideration of buildability of designs.

7 Contractual arrangements

Contractual arrangements between **all** parties involved – with clear exposition of relationships, and responsibilities, including necessary consultation with respect to effective:

7.1 control;

7.2 communication;

7.3 co-operation;

7.4 definition and assessment of competence;

include details of responsibilities accepted by the parties involved, and resources allocated to ensure Health and Safety Risk Management is focused on those parties best placed to exercise effective risk management and control.

Organisation and management issues

8 Management systems

Particulars sufficient to demonstrate the adequacy of the management systems to meet legal obligations, with particular reference to:

8.1 planning with special reference to contingency responses to unfavourable situations that might be disclosed by observations during construction;

8.2 organisation and arrangements for safety policy implementation;

8.3 duties of personnel:

.1 organisational diagram showing lines of communication and reporting

.2 job descriptions for all personnel

8.4 control and supervision – by whom and how, and to what level of expertise;

8.5 arrangements for work programme allowing for sufficient time to perform works to an agreed quality standard;

8.6 communication arrangements in house and with others involved in the project;

8.7 training, means of ensuring competence and arrangements for continued assessments of these needs, extent to which reliance is placed on experience;

8.8 monitoring of preventative and protective measures;

8.9 review and audit of above procedures – feedback loops;

8.10 management of 'human factors' and related safety culture issues;

8.11 staffing levels – including out of hours cover;

8.12 briefing of site personnel on the basis and intent of the design and critical components;

8.13 management of sub-contractors and others on site;

8.14 arrangements for consultation with workers;

8.15 arrangements for the investigation of accidents and dangerous occurrences.

9 Quality assurance and control

9.1 procedures for design, specification and construction management of any remedial work;

9.2 deviation and defect management systems;

9.3 control of the period between excavation and the installation of support work, and the availability of support materials;

9.4 support system design:

.1 quality control and strength/gain characteristics of shotcrete;

.2 thickness and profile control of shotcrete;

.3 strength and stiffness of support;

.4 effect of additives in the shotcrete;

.5 quality of joints, connections and support details;

.6 instrumentation of radial and tangential loads and lining deformation;

.7 specification of geometric tolerances;

.8 use of dowels and any other means of ground improvement;

.9 sampling and testing regime.

9.5 in-situ testing regime.

Technical support

10 Design verification and trials

10.1 careful choice of appropriate tunnelling methods, and geometries;

10.2 clear engineering goals of trial works with full and open discussion and evaluation and interpretation of results;

10.3 extent of read-over to main project including calibration of computer programmes;

10.4 statement of assumptions used in main design, with a statement on rationale, and methodology for continuing validation and development;

10.5 sensitivity analysis of assumptions;

10.6 application to 'multi-tunnel' working or work adjacent to shafts or voids;

10.7 tolerances including analysis of intermediate states as well as final analysis on completion.

11 Details of site instrumentation and monitoring

11.1 design of measurement and monitoring systems – both on and off site;

11.2 selection of equipment, location, validation, verification and calibration;

11.3 action levels and procedures at stages of construction together with action plans or emergency action plans for responding when parameters approach outside acceptable levels;

11.4 establishment of predicted and acceptable ranges or limits for parameters that are due to be observed, at each stage of construction;

11.5 results and interpretation arrangements with details of information evaluation in real time, frequency of reporting etc;

11.6 frequency of monitoring;

11.7 details of data acquisition, processing, presentation and reporting.

12 Emergency procedures and contingency plans

12.1 identify potential failure modes and production of emergency procedures and contingency plans including structural support and pumping where appropriate;

12.2 command and control arrangements;

12.3 emergency response times;

12.4 evacuation procedures – on site and off site as necessary;

12.5 procedure initiation arrangements (24 hour basis);

12.6 validation (table top exercises etc);

12.7 liaison arrangements with emergency services, utilities etc.

Appendix 3

List of relevant UK health and safety legislation

- 1 The Health and Safety at Work Act 1974 (c.37)
- 2 The Management of Health and Safety at Work Regulations 1992 (SI 1992 No. 2051)
- 3 The Approved Code of Practice to The Management of Health and Safety at Work Regulations 1992 (ISBN 0 7176 0412 8)
- 4 The Construction (Design and Management) Regulations 1994 (SI 1994 No. 3140)
- 5 The Approved Code of Practice to The Construction (Design and Management) Regulations 1994 'Managing Construction for Health and Safety' (ISBN 0 7176 0792 5)
- 6 The Construction (General Provisions) Regulations 1961 (SI 1961 No. 1580 as amended)
- 7 The Construction (Lifting Operations) Regulations 1961 (SI 1961 No. 1581 as amended)
- 8 The Construction (Working Places) Regulations 1966 (SI 1966 No. 94 as amended)
- 9 The Construction (Health and Welfare) Regulations 1966 (SI 1966 No. 95 as amended)
- 10 Construction (Head Protection) Regulations 1989 (SI 1989 No. 2209 as amended)

Appendix 4

The principles of prevention and protection

(Appendix 2 of the CDM Approved Code of Practice)

The principles of prevention and protection are:

- (a) **If possible, avoid the risk completely**, by using alternative methods or materials.
- (b) **Combat risks at source**, rather than by measures which leave the risk in place but attempt to prevent contact with the risk.
- (c) **Wherever possible, adapt work to the individual**, particularly in the choice of work equipment and methods of work. This will make work less monotonous and improve concentration, and reduce the temptation to improvise equipment and methods.
- (d) **Take advantage of technological progress**, which often offers opportunities for safer and more efficient working methods.
- (e) **Incorporate the prevention measures into a coherent plan** to reduce progressively those risks which cannot altogether be avoided and which takes into account working conditions, organisational factors, the working environment and social factors. On individual projects the health and safety plan will act as the focus for bringing together and co-ordinating the individual policies of everyone involved. Where an employer is required under the HSWA to have a health and safety policy, this should be prepared and applied by reference to these principles.
- (f) **Give priority to those measures which protect the whole workforce or activity** and so yield the greatest benefit, ie give collective protective measures such as suitable working platforms with edge protection, priority over individual measures, such as safety harnesses.
- (g) **Employers and the self-employed need to understand what they need to do**, eg by training, instruction, and communication of plans and risk assessments.
- (h) **The existence of an active safety culture affecting the organisations responsible for developing and executing the project needs to be assured.**

Glossary of terms

BENCH – The mid-section(s) between the crown and invert in the stepped excavation of a NATM tunnel excavated in horizontally stepped stages.

CDM – The Construction (Design and Management) Regulations 1994.

CONVERGENCE – Changes in the distance between fixed points on a (cross-section of a) tunnel lining as a result of loading on the lining.

CONTINGENCY PLAN – Predetermined arrangements for dealing with events such as face collapse or lining failure.

COMPENSATION GROUTING – A system by which grout is injected into the ground above a tunnel and below man-made surface features. The intention is to ameliorate the effects of surface settlement caused by ground loss due to the tunnelling work.

COMPETENT PERSONS – Persons who have the necessary training and experience or knowledge and other qualities to enable them to perform the task in hand safely and without risks to health.

COMPETENT GROUND – A term applied to ground which has the necessary inherent strength required by the design of the tunnelling system.

CROWN – The upper-section in the stepped excavation of a NATM tunnel excavated in 2 or more horizontally stepped stages. It is the first section to be excavated.

CUT AND COVER – A system of tunnel construction using an open cut technique rather than mining. A temporary covering at ground level may be provided for the passage of traffic or environmental reasons.

DAYLIGHT COLLAPSE – A collapse which progresses up through the ground and reaches the surface where a crater is normally formed. Daylight may sometimes be seen from inside the tunnel following the collapse.

DEFORMATION – A change in shape of a structure or part of a structure or the ground. Usually refers to the change in shape with respect to load and time of the inner profile of the NATM lining.

DESIGN – A term defined under CDM as ‘in relation to any structure includes drawing, design details, specification and bills of quantities (including specification of articles or substances) in relation to the structure’.

DRIFT – Usually means the driven section of part of the full NATM cross-section.

DUMPLING – Ground left against an excavated face of a tunnel to provide temporary support to it.

ELEPHANT’S FEET – Enlarged bearing areas at the bases of partially constructed linings, normally of the crown section.

EMERGENCY PLAN – Predetermined arrangements for mitigating the possible effects of an unplanned event which may create unacceptable risk.

EROSION FEATURE – A natural feature in the ground which has formed due to erosion of the ground in geological times. Often these features are refilled with very loose material and hence pose a hazard in any tunnelling works.

FOREPOLING (SPILING) – A ground improvement measure carried out by inserting bars rods or tubes at the face so as to form a splayed arch ahead of the tunnel. It can involve areas of jet grouting or ground freezing. Previously, the term was used more narrowly. It related to poling boards driven on a splay ahead of the face of an excavation. The boards were secured by wedges on timber sets.

GALLERY – One of a number of tunnels driven sequentially and in parallel. They are progressively connected one with another to form a single tunnel of larger cross-section. May also be called drifts.

GRIDER or RIB (LATTICE) – A steel (lattice) arch normally erected at regular centres as the tunnel advances. It is sequentially erected from component parts as the lining is progressively formed and encapsulated within the shotcrete. It is normally provided in the crown section to provide temporary protection to miners from the risk of collapse. The girders can be fully circumferential.

GROUND IMPROVEMENT – A process intended to improve the engineering properties of the ground. Ground water lowering and ground freezing are examples of techniques which can be used in conjunction with tunnelling.

HAZARD – Something with the potential for harm.

HEADING – The area at the front of the tunnel construction beyond the completed NATM ring.

HEAVE – Ground movement in a tunnel in the form of upward deflection of the invert.

HUMAN FACTORS – Includes the perceptual, mental and physical capabilities of people and the interactions of individuals with their job and working environments, the influence of equipment and system design on human performance, and above all, the organisational characteristics which influence safety related behaviour at work.

HSWA – The Health and Safety at Work Act 1974.

INSITU – Cast in place.

INVERT – (1) The lowest section of a tunnel.

INVERT – (2) The lowest section in a stepped excavation of an NATM tunnel excavated in horizontally stepped bands. It is the last section to be cut. A temporary invert may be cut on occasions in large tunnels and is differentiated from a bench cut by the temporary closure of the ring.

LINING, NATM PRIMARY – The first lining formed of shotcrete and normally reinforced with mesh and lattice girders.

LINING, SECONDARY – A lining formed within the primary lining.

MHSW – The Management of Health and Safety at Work Regulations 1992.

MONITORING – A method involving engineering measurements and direct visual observation with the purpose of studying the performance of a lining and ground structure.

N.A.T.M. or NATM – See text - part 1.

OBSERVATIONAL METHOD – See definition – part 5.

PILOT TUNNEL – A tunnel driven with a cross-section smaller than that finally intended.

PLANNING SUPERVISOR – A person (or other legal entity) appointed by the client under CDM to act in this capacity for the project.

PORTAL – An entrance to a tunnel.

PRINCIPAL CONTRACTOR – A person (or other legal entity) appointed by the client under CDM to act in this capacity for the project.

REBOUND (MATERIAL) – Loose material from the shotcreting process which has not adhered to the excavated surface nor the panel of shotcrete being formed. It can provide planes or zones of weakness in the shotcrete lining if it sets, is not cleared away and is subsequently incorporated into later panels.

RING CLOSURE – The point at which the full annular cross-section of the NATM tunnel has been completed.

RISK – Expresses the likelihood that a hazard may be realised. It is also concerned with the consequences.

SHOTCRETE – A concrete mix containing **admixtures** which is pumped to a nozzle where it is sprayed onto a surface at pressure.

SIDE GALLERY – A gallery constructed to one side of the intended final cross-section of the tunnel. In all but the largest tunnels, there may typically be one or two side galleries or drifts.

STANDUP TIME – The time that an unsupported excavated face remains stable.

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